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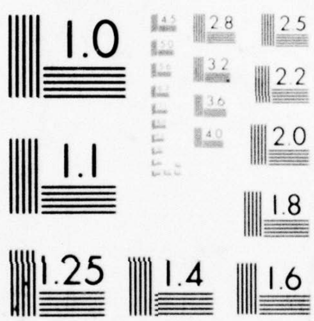

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TECHNICAL REPORT H-77-6

SPILLWAY VIBRATION, PRESSURE, AND VELOCITY MEASUREMENTS, OZARK LOCK AND DAM, ARKANSAS RIVER, ARKANSAS

by

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April 1977
Final Report

Prepared for U. S. Army Engineer District, Little Rock
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Ozark Lock and Dam	Vibrations

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Tests were conducted in bay 8 of the low-overflow spillway at Ozark Dam, Arkansas River, Arkansas, in September 1974 to study vibrations and pressure fluctuations as related to flow through the spillway. Pressures were measured on the spillway sill to determine whether fluctuations are correlated with structural vibrations. Velocity distributions were measured to study boundary layer development and to determine an equivalent roughness for the spillway surface. Gate vibrations were measured to attempt to confirm model results.

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20. ABSTRACT (Continued)

Pressure fluctuations on the low overflow spillway did not exhibit a root-mean-square (RMS) value large enough to be considered as a source of excitation of spillway vibration. The structure appeared to be vibrating at a natural frequency of 2.7 cps. Structural vibration amplitude was relatively small. Gate vibrations appeared to be independent of opening. The equivalent sand grain roughness K_s determined for the Ozark spillway (0.0061 ft) supplements previous data. Theoretical boundary layer thicknesses agree with the measured velocity profiles.

PREFACE

The prototype tests described herein were sponsored by the U. S. Army Engineer District, Little Rock. The analysis was conducted and the report prepared under Corps of Engineers Engineering Study 805, "Hydraulic Prototype Tests."

Instrumentation and personnel for conducting the measurements were provided by the U. S. Army Engineer Waterways Experiment Station (WES). WES participants were Messrs. C. A. Pugh, E. B. Pickett, J. E. Hall, and J. C. Ables. Little Rock personnel assisting in the measurements were Messrs. J. Clements and G. Wilbur. Acknowledgment is also made to project personnel who assisted during the tests. This report was prepared by Mr. Pugh under the direct supervision of Mr. E. D. Hart, Chief, Prototype Branch, and the general supervision of Mr. E. B. Pickett, Chief, Hydraulic Analysis Division, and Mr. H. B. Simmons, Chief, Hydraulics Laboratory.

COL G. H. Hilt, CE, and COL J. L. Cannon, CE, were Directors of WES during the investigation and the preparation and publication of this report. Mr. F. R. Brown was Technical Director.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
square feet	0.09290304	square metres
cubic feet	0.02831685	cubic metres
cubic feet per second	0.02831685	cubic metres per second
pounds (force) per square inch	6.894757	kilopascals
pounds (force) per square foot	47.88026	pascals
feet per second	0.3048	metres per second
slugs per cubic foot	515.3788	kilograms per cubic metre
Fahrenheit degrees	0.555	Celsius degrees or Kelvins*
kilowatt-hour	3,600,000	joules

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* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = 0.555 (F - 32). To obtain Kelvin (K) readings, use: K = 0.555 (F + 459.67).

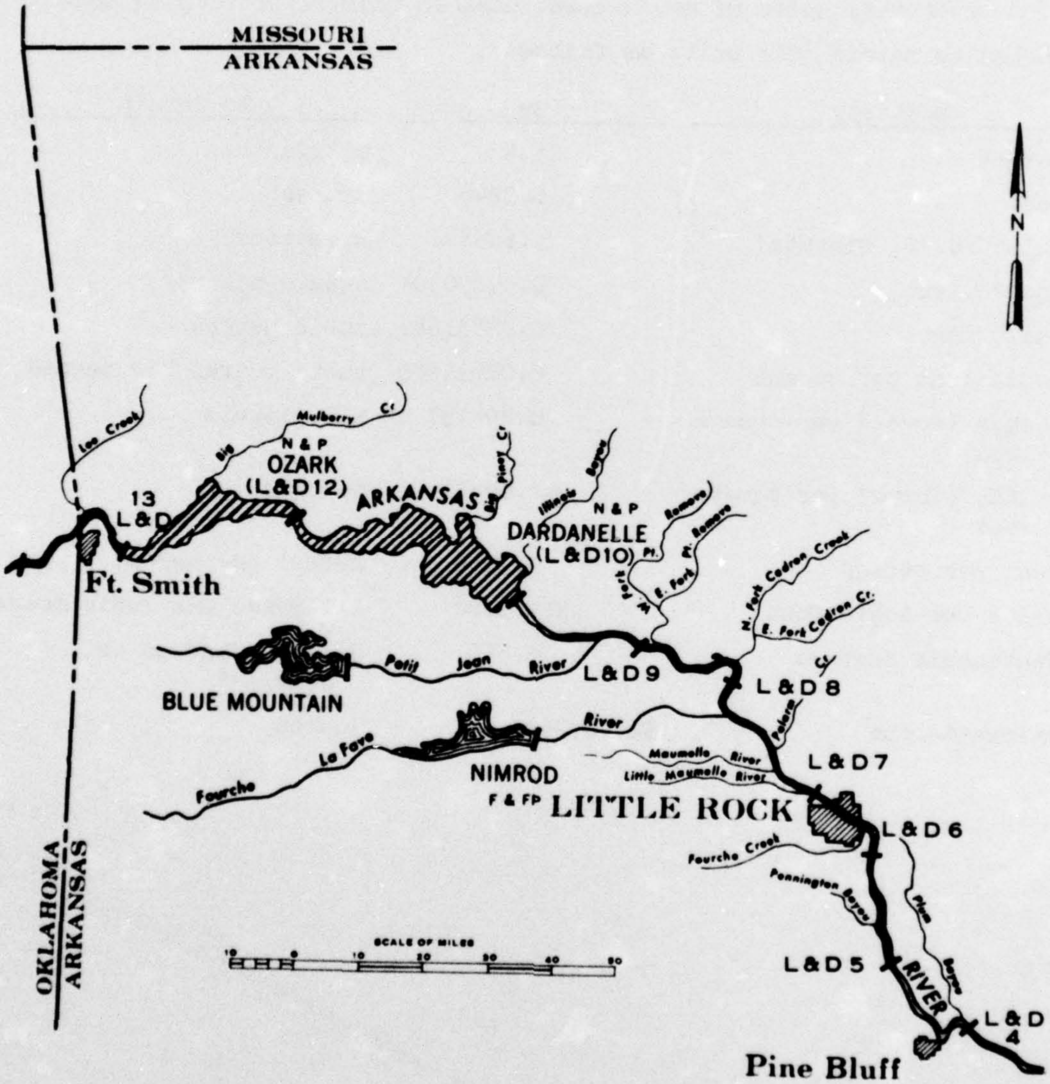

Figure 1. Vicinity map, Ozark Lock and Dam

SPILLWAY VIBRATION, PRESSURE, AND VELOCITY MEASUREMENTS
OZARK LOCK AND DAM, ARKANSAS RIVER, ARKANSAS

PART I: INTRODUCTION

Pertinent Features of the Project

1. Ozark Lock and Dam (Lock and Dam 12) is one of the major units in the multipurpose project for improvement of the Arkansas River and its tributaries in Arkansas and Oklahoma. Project purposes include serving navigation, producing hydroelectric power, affording additional flood control, and providing related benefits such as public recreational facilities and fish and wildlife conservation.

2. The structures are located at mile 308.9* (1940 survey) of the Arkansas River, 1.4 miles downstream from the Highway 23 bridge crossing the river at the city of Ozark (Figure 1). The reservoir extends approximately 57.6 miles upstream.

Description of Structures

3. The structures consist of a lock on the left bank, an 890-ft-long dam, and a hydroelectric plant on the right overbank (Figure 2). The lock has a 110- by 600-ft lock chamber, 600-ft guide walls upstream and downstream on the river wall, and 60-ft guide walls on the land wall. The lock is designed for a lift of 34 ft with upper pool at el 372** and the lower pool at el 338. The maximum lift is 37 ft when the lower pool drops to el 335. The dam consists of fifteen 50-ft-wide spillway bays and fourteen 10-ft-wide piers. The spillway is controlled with fifteen 50-ft-wide by 46-ft-high conventional tainter gates with the sills set at el 327. The powerhouse facilities consist of four

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

** All elevations (el) cited herein are in feet above mean sea level.

Figure 2. Ozark Lock and Dam

slant turbine units with a station capacity of 100,000 kw. Excavated channels lead to the headbay and tailrace.

Purpose and Scope of Study

Purpose

4. At the request of the U. S. Army Engineer District, Little Rock, the U. S. Army Engineer Waterways Experiment Station, (WES) conducted a series of tests at Ozark Lock and Dam. Specific objectives of these tests were to:

a. Study boundary layer development on a flat spillway crest.

b. Determine an equivalent sand grain roughness for the spillway surface.

c. Determine if pressure fluctuations on the spillway sill are a possible mechanism for excitation of spillway vibration.

d. Determine gate vibration characteristics.

e. Determine single bay discharge characteristics for full and partial gate openings.

5. Very little information on the full-scale performance of low-sill spillways is available. Data were gathered at Ozark for use in developing design criteria for future projects of the Corps of Engineers.

Scope

6. From 16 to 20 September 1974, 22 tests were conducted in two parts. The first set of test measurements (tests 1-7) consisted of the following:

a. Pressure differential measurements between a reference pressure and the ten total head and two static head tubes on each of three velocity probe assemblies designated A, B, and C and located on the spillway sill as shown in Plate 1.

b. Measurement of the reference pressure (service water).

c. Acceleration measurements at five locations in and on spillway pier monolith 8.

d. Acceleration measurements at two locations on gate 8.

e. Auxiliary measurements including:

(1) Pool elevation.

(2) Tailwater elevation.

(3) Gate opening.

(4) Time.

(5) Velocity and elevation of water surface just upstream from gate 8.

7. The second set of tests (8-22) consisted of the following:

a. Measurement of average and fluctuating pressures on three pressure cells designated A, B, and C and located in the same mounting boxes as velocity probes A, B, and C described in paragraph 6a.

b. Spillway, pier, and gate acceleration measurements at the locations described in paragraphs 6c and 6d.

c. Auxiliary measurements as described in paragraph 6e.

Background

Spillway vibration

8. Pressures were measured on the spillway sill at Ozark Dam under various flow conditions to determine whether these pressure fluctuations correlated with vibrations measured on the spillway. Prototype tests at Chief Joseph Dam indicated no hydraulically excited pressure fluctuations of sufficient magnitude existed that could be considered a possible source of structural vibration; however, Chief Joseph has a high-overflow-type spillway.[1] The mass of fluid in motion over a high overflow spillway is small compared with the effective mass of the spillway and its foundation. Therefore, vibration of high overflow spillways has not been of particular concern. For a low overflow spillway, the mass of water over the spillway is of the same order of magnitude as the mass of the spillway itself. Thus, if some flow instability exists, structural vibration of the spillway becomes a distinct possibility. There have also been several undocumented oral reports of vibration of low-crest spillways for flows with heads exceeding the spillway height.[2]

Gate vibrations

9. Vibration problems have been encountered with the gates at Locks and Dams 2-6 and 10 on the Arkansas River.[3] Although vibrations of the prototype gates at Lock and Dam 12 (Ozark) had not been reported, gates with similar lip-and-seal configurations were reported to vibrate at small gate openings. As a result, the Ozark gate design was model-tested for vibrations.[4] The model gate did not vibrate at any opening. Prototype gate vibrations were measured to confirm model results and to determine gate vibration characteristics.

10. Discharge was not measured because the time required for flow stabilization and discharge measurements in the Dardanelle Lake pool (downstream from Ozark) would have been prohibitive for the tests. Also, the measurement accuracies of the low velocities would have been questionable.

Related Studies and Model Investigations

11. The Iowa Institute of Hydraulic Research conducted two vibration studies[2,5] under contract for the WES. One study[2] concerns flow-induced vibrations of hydraulic control gates; the other[5] deals with pressure fluctuations on low-ogee crest spillways relevant to flow-induced structural vibrations. Another study was on spillway gate vibrations on Arkansas River dams.[3] Studies done at WES include an investigation on spillway gate vibrations[4] and a model study on a spillway for a typical low-head navigation dam.[6]

PART II: TEST FACILITIES AND EQUIPMENT

Mounting Boxes

12. During construction of the dam three mounting boxes for either velocity probes or pressure transducers were installed between the tainter gate and stop log slot near the center line of spillway bay 8. The mounting boxes were staggered in plan (see Plate 1) to prevent erroneous readings at a downstream probe due to the wake of an upstream probe. Conduits connecting the mounting boxes with the inspection gallery in the dam were used to pass tubes and electrical cables from the instruments to the recording equipment in the inspection gallery.

Velocity probes

13. Three velocity probe assemblies (designed and fabricated at WES) were used to measure velocities at ten points ranging from 1/2- to 11-1/4 in. vertically above the spillway face. Two probe assemblies are shown in Figure 3. The eight short tubes on each probe transmit

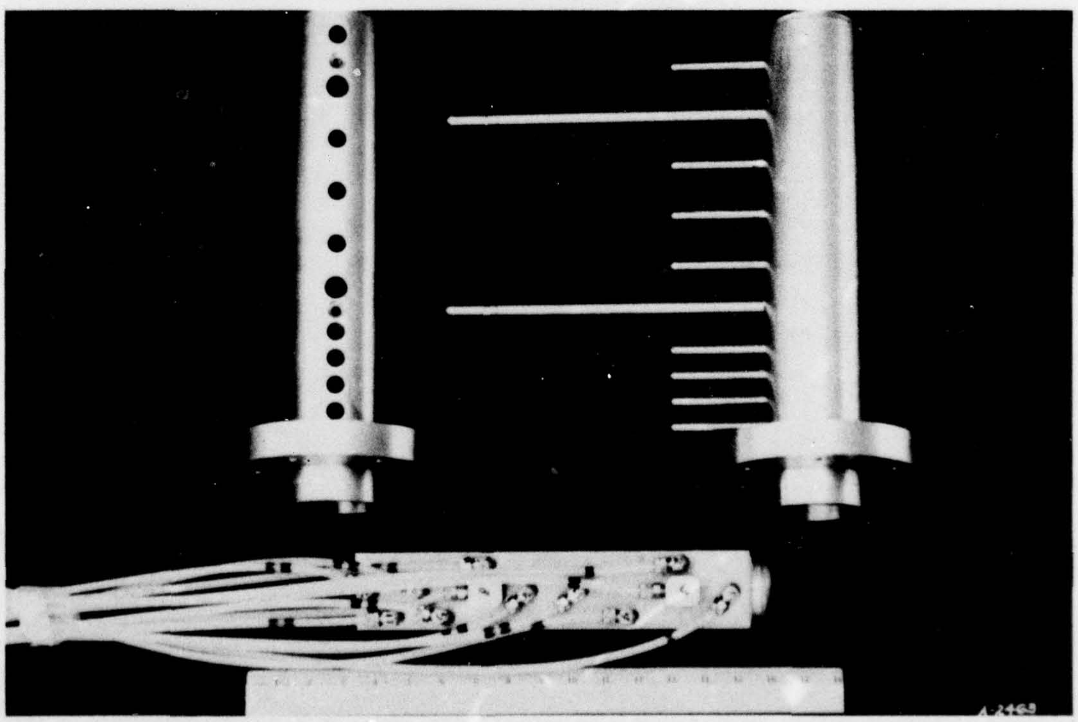

Figure 3. Spillway velocity probes (one assembled and one disassembled)

stagnation pressures through the plastic lines to a recording location. The two long tubes on each probe encase one stagnation and one static pressure line. The velocity head was obtained by subtraction of the static pressure from the stagnation pressure.

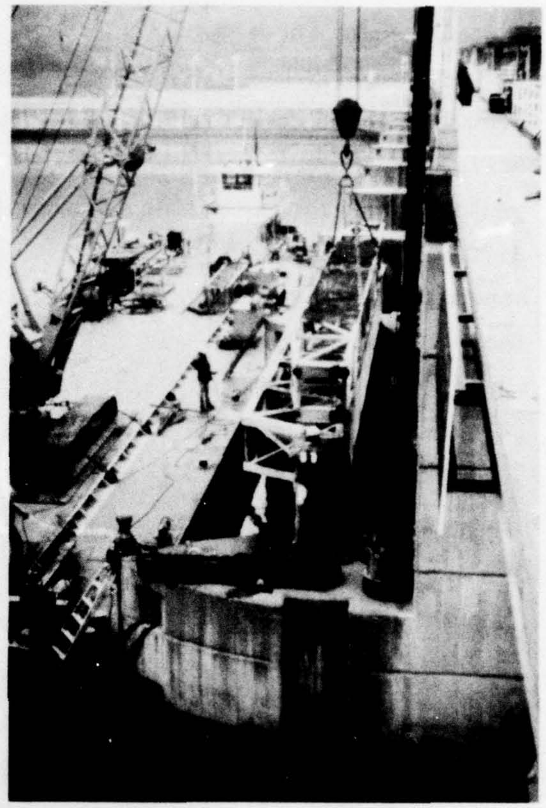

Figure 4. Installation of stop logs

14. Stop logs were installed in spillway bay 8 by a crane (Figure 4). The water between the stop logs and tainter gates was then pumped out. The crane lowered the men and equipment to the spillway sill in a cage. The area around the mounting boxes was sealed off and the instruments were installed (Figure 5). A man in the inspection gallery (below spillway bay 8) pulled the instrument leads through the embedded conduits.

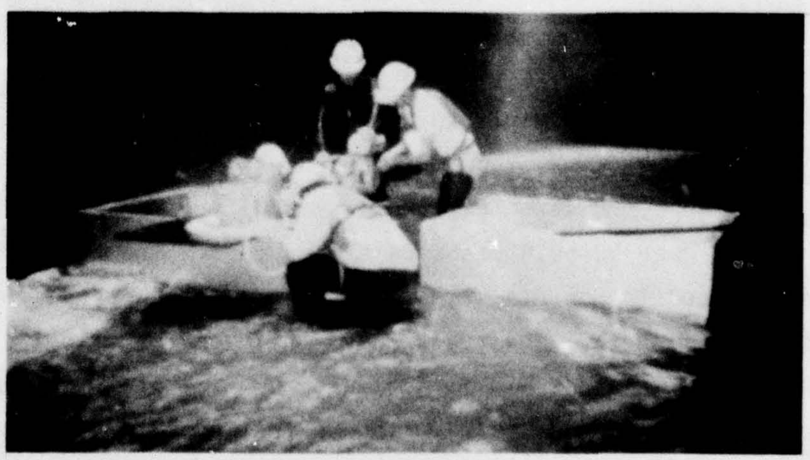

Figure 5. Installation of instruments between the stop logs and tainter gate of spillway bay 8

15. Pressures from each line on each velocity probe were recorded for tests 1-7. The static and stagnation pressures were measured with Consolidated Electrodynamics Corporation (CEC) ±15- and ±10-psi differential pressure transducers (Figure 6). A reference pressure from the project (service waterline) was applied to the opposing side of each differential transducer. This reference pressure was measured separately with a mercury well manometer before and after each test. The reference pressure was slightly more than the pool pressure. As a check, each pressure was also read from a bourdon-type pressure gage (Figure 6).

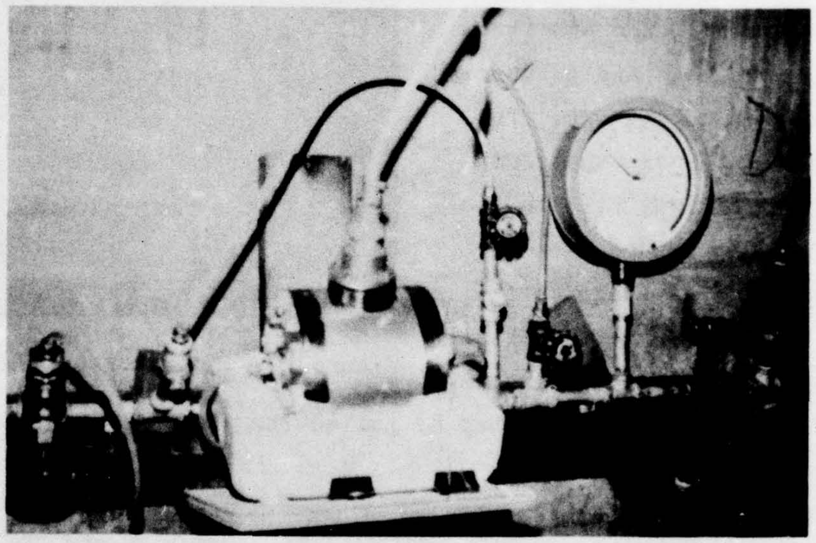

Figure 6. Differential pressure transducer and bourdon gage mounted on manifold in inspection gallery

Pressure transducers

16. The pressures were measured with CEC type 4-312, 1/2-in.-diam, unbonded strain gage 50-psia pressure transducers. The three transducers were flush-mounted in boxes A, B, and C with use of the procedures described in paragraph 14. The transducers replaced the velocity probes that were used during tests 1-7. Duplicate cover plates for the mounting boxes were drilled and tapped prior to the tests to accommodate the pressure transducers.

Accelerometers

17. Accelerations were measured with Statham Model A-3, 0- to 5-g's accelerometers (Figure 7). Five accelerometers were mounted on spillway and pier monolith 8 and two were mounted on tainter gate 8. (See Plate 1 for mounting locations).

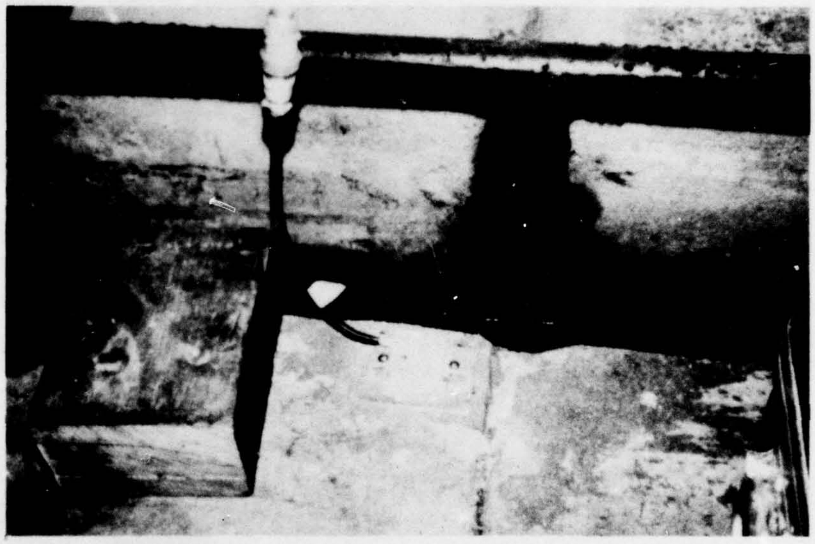

Figure 7. Accelerometer 1-V (measures vertical accelerations) mounted in inspection gallery

Recording Equipment

18. The signals from the pressure transducers and accelerometers were amplified with WES-fabricated amplifiers and recorded with a Sangamo 14-channel magnetic data tape recorder. The signals were then played back on a CEC 5-119 V P4, direct-write oscillograph recorder (Figure 8).

Other Measurements

19. A Morgan Model 22 Optical Flowmeter was used to measure surface velocities at the center of bay 8 (Figure 9). The upper pool,

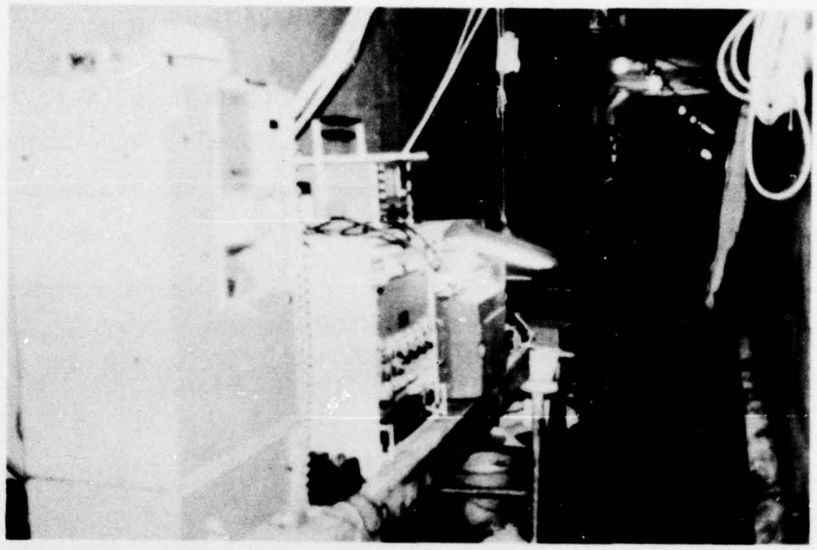

Figure 8. Recording equipment in inspection gallery; from left to right--magnetic tape recorder, amplifiers, and oscillograph recorder (velocity probe manifold in background)

Figure 9. Optical flowmeter mounted on spillway bridge above spillway bay 8

lower pool, and gate opening were all obtained from project gages. The actual position of the gate was also measured to check the accuracy of the gate opening indicator. The indicator readings checked closely with the actual gate opening.

PART III: TEST CONDITIONS AND PROCEDURES

Conditions

20. As stated previously, 22 tests were conducted in two parts at Ozark. The first seven tests were primarily concerned with determining velocity profiles. Accelerations were also measured during these tests to determine the amount of vibration so the amplification could be set optimally for the second set of measurements. Tests 8 and 9 were calibration check tests on the pressure transducers. During tests 10-22, average and fluctuating pressures on the spillway and accelerations on monolith 8 and tainter gate 8 were measured simultaneously. The following tabulation lists the test conditions:

Test No.	Gate Opening ft	Discharge cfs	Pool ft-msl	Tailwater ft-msl	Date Sep 1974	Time	Comments
1	1.0	1,034*	369.60	342.20	17	1600	Tests 1-7; velocities measured on the spillway crest
2	4.0	6,193*	369.68	341.70	17	1640	
3	8.0	12,918	369.20	341.75	17	1800	
4	12.0	17,944	368.75	342.25	17	1852	
5	17.0	23,351	368.42	345.60	17	1925	
6	25.0	30,991	368.52	-	17	2015	
7	32.5	33,485	368.65	342.30	17	2050	
8	0.0	-	**	**	18	1327	Tests 8-9; calibration and zero levels
9	0.0	-	370.90	339.05	18	1500	
10	1.0	1,161*	371.20	339.15	19	0835	Tests 10-22; pressure fluctuations on the spillway crest and accelerations on spillway monolith 8 and tainter gate 8
11	2.0	2,909*	371.20	339.22	19	0855	
12	4.0	6,694*	371.20	339.30	19	0905	
13	6.0	10,305	371.14	-	19	0910	
14	8.0	13,247	371.08	-	19	0945	
15	10.0	16,006	371.02	340.05	19	0955	
16	15.0	22,079	370.88	340.40	19	1005	
17	15 to 20	†	-	-	19	1025	
18	20.0	27,427	370.65	340.90	19	1037	
19	25.0	32,120	370.45	341.45	19	1045	
20	30.0	34,500	369.95	342.50	19	1058	
21	34.0	35,500	369.55	343.48	19	1107	
22	34 to 0	†	369.90	342.25	19	1116 to 1153	

* Partially submerged flow.
** Dewatered between bulkhead and gate.
† Varies.

Procedures

21. Procedures for tests 1-7 were as follows:

<u>a</u>. Install stop logs; dewater and install velocity probes.

<u>b</u>. Install accelerometers.

<u>c</u>. Remove stop logs.

<u>d</u>. Open the tainter gate to the desired position.

<u>e</u>. Open each line on each velocity probe assembly (separately) to a differential pressure transducer and record on the oscillograph. Also record the bourdon-type gage pressure for each line.

<u>f</u>. Measure the reference pressure with the mercury well manometer and record.

<u>g</u>. Record accelerations on magnetic tape for 5 min.

<u>h</u>. Record the upper pool, lower pool, gate opening, surface velocity, and the distance from the bridge to the water surface in spillway bay 8.

22. Procedures for tests 8-22 consisted of the following:

<u>a</u>. Install stop logs, dewater, remove velocity probes, and install pressure transducers. Record at atmospheric pressure for transducer calibrations zero.

<u>b</u>. Remove stop logs.

<u>c</u>. Record pool pressure with the transducers as a calibration check.

<u>d</u>. Open the gate to the desired position.

<u>e</u>. Record accelerations and pressures on magnetic tape simultaneously for 5 min.

<u>f</u>. Record the upper pool, lower pool, gate opening, surface velocity, and the distance from the bridge to the water surface in spillway bay 8.

PART IV: TEST RESULTS AND ANALYSIS

Velocity Profiles

23. The velocity profiles at probes A, B, and C for tests 1-7 are shown in Plates 2-8; the velocities are listed in Table 1. The theoretical boundary layer thickness δ* was computed according to the following equation:

$$\delta = X \frac{0.377}{R_x^{1/5}} \tag{1}$$

where

X = the distance downstream from the leading edge of the spillway (10 ft at A, 19 ft at B, and 28 ft at C)

and

R_x = the Reynold's number = $(U_\infty X/\nu)$; with

U_∞ = free stream velocity

ν = kinematic viscosity (1.46×10^{-5} ft^2/sec at $60^{\circ}F$)

The following tabulation lists the computed boundary layer thicknesses:

Test No.	Boundary Layer Thickness, ft Probe A	Probe B	Probe C
1	0.1397	0.2322	0.2982
2	0.1365	0.2194	0.2902
3	0.1503	0.2263	0.3068
4	0.1345	0.2127	0.2787
5	0.1313	0.2102	0.2801
6	0.1343	0.2161	0.2829
7	0.1320	0.2166	0.2867

---

* For convenience, symbols and unusual abbreviations are listed and defined in Appendix A.

These computed values of δ are plotted in Plates 2-8. Another way to determine δ is to select the point where $U = 0.99\ U\infty$. Figure 10 depicts boundary layer growth. For gate openings more than 8 ft, the theoretical boundary layer thickness is relatively close to the $0.99\ U\infty$ point in the profiles.

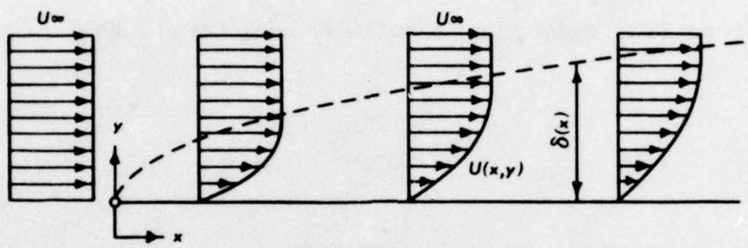

Figure 10. Theoretical boundary layer development

24. The universal velocity distribution law

$$\frac{U}{U^*} = 5.75 \log \frac{y}{K_s} + 8.5 \tag{2}$$

has been shown to describe the velocity gradient near a rough wall[7] where

U = local velocity, ft/sec

$U^* = \sqrt{\tau o/\rho}$ where τo is the boundary shear stress, lb/ft^2 and ρ is the fluid density, $slug/ft^3$

y = distance from wall, ft

K_s = equivalent sand grain roughness, ft

Equation 2 can also be written in the general form

$$U = A \log y + B \tag{3}$$

where

$$A = 5.75\ U^* \tag{4}$$

and

$$B = U^*(8.5 - 5.75 \log K_s) \tag{5}$$

The velocity data for test 7 (free flow) are plotted in semilogarithmic form in Figure 11; A is the slope of the curve near the wall. The local skin friction coefficient c'_f is defined in general, as

$$c'_f = \frac{\tau o}{\frac{1}{2}\rho U_\infty^2} \tag{6}$$

and for fully rough flow, is evaluated from

$$c'_f = \left(2.87 + 1.58 \log \frac{X}{K_s}\right)^{-2.5} \tag{7}$$

Combining Equations 6 and 7

$$U^* = \left[\frac{1}{2}\left(2.87 + 1.58 \log \frac{X}{K_s}\right)^{-2.5} U_\infty^2\right]^{1/2} \tag{8}$$

K_s can then be solved for directly since X and U_∞ are known and U^* is known from Equation 4. The following values were determined for K_s:

Equivalent Sand Grain Roughness, ft			
Probe A	Probe B	Probe C	Avg
0.0132	0.0013	0.0038	0.0061

25. According to Schlicting,[7] the equivalent roughness decreases with distance downstream. This descreasing roughness is attributed to the increasing thickness of the laminar boundary layer with distance downstream. This factor accounts for the decrease in K_s from probe A to probe C, since the slopes of the log-linear velocity profiles at A and C were approximately equal.

26. Hydraulic Design Criteria (HDC) Sheet 631[8] suggests design

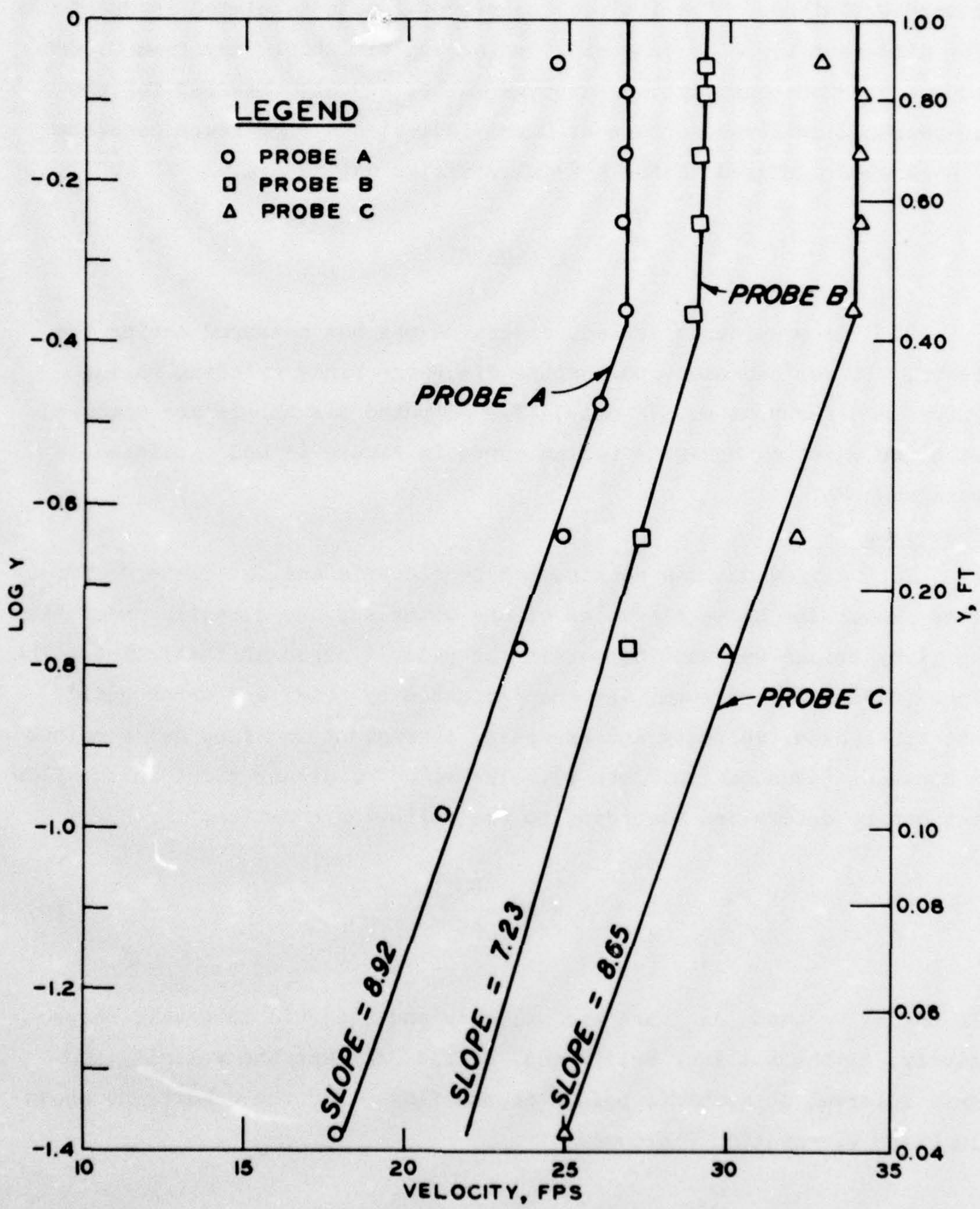

Figure 11. Log-linear velocity profile plots for test 7

values for K_s ranging from 0.002 to 0.007 for open channel flow over concrete finishes. The limited experimental data tabulated in Sheet 631 for different types of concrete forming and finishing vary from 0.0006 to 0.005. Consequently, the average value, 0.0061, obtained for the 10-year-old spillway surface at Ozark indicates a very rough concrete finish when compared to the hydraulic design data above.

Discharge

27. As previously stated, discharge was not measured during the tests. It was necessary to compute discharge since existing rating curves are for pool el 372 only. The computed discharges are compared with the existing one-gate rating curve in Figure 12 and tabulated in paragraph 20.

Free flow

28. A flow net was constructed by electric analog (Plate 9) for free flow. The known elevation of the water surface directly under the spillway bridge was used to obtain the velocity head at that point. The free surface of the water was then adjusted by trial and error until the total head (velocity and pressure) throughout the flow net remained a constant (as shown in Plate 9). The velocity at any point in the flow net can be determined according to the following equation:[9]

$$V = KV_o \frac{\Delta n_o}{\Delta n} \tag{9}$$

in which V_o and Δn_o are the velocity and the grid interval, respectively, at the spillway bridge and V and Δn are the velocity and grid interval at specific points in the flow. For the conditions shown in Plate 9, equation 9 becomes

$$V = \frac{199.43}{\Delta n} \tag{10}$$

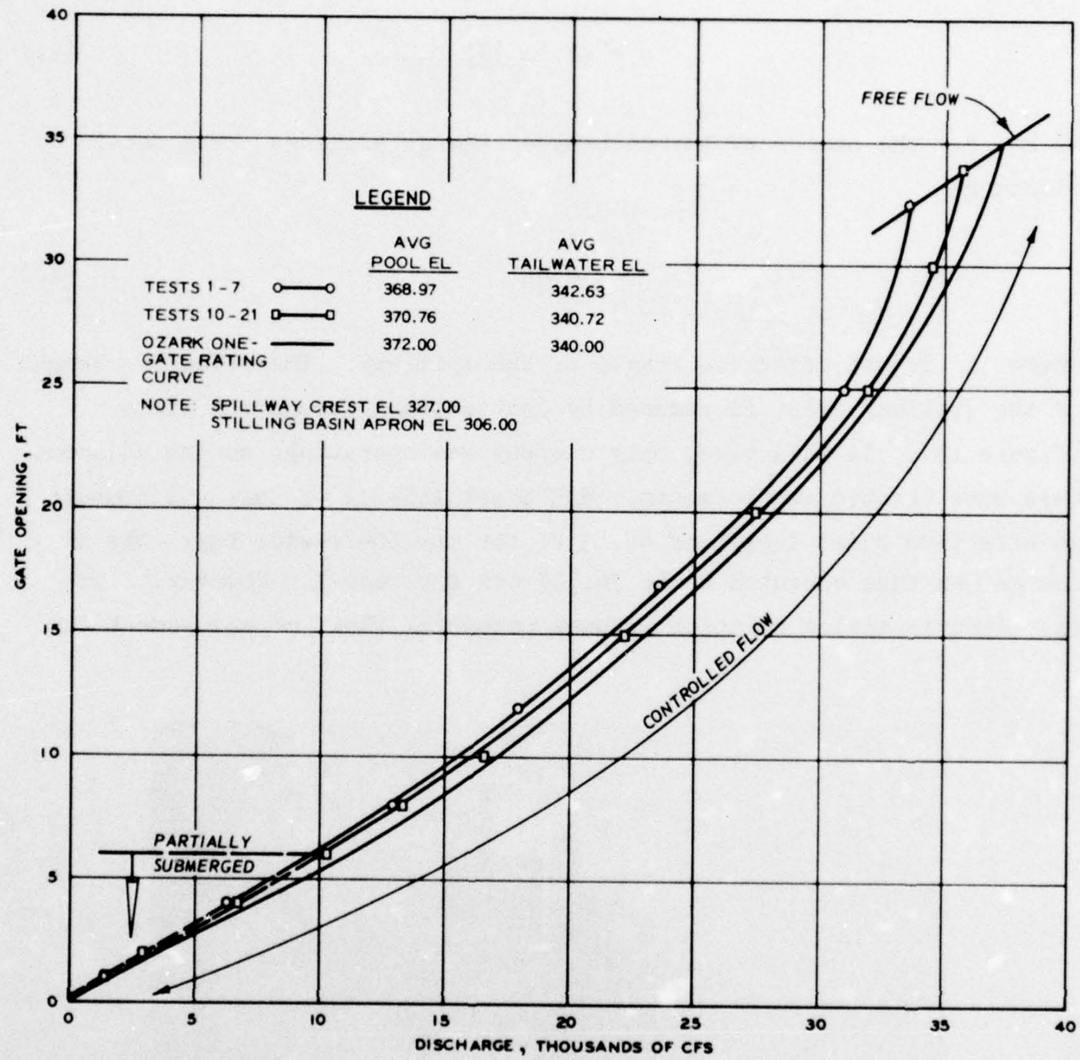

Figure 12. Existing one-gate rating curve and discharges computed for Sep 1974 tests

In using equation 10 the grid spacing, Δn , is in feet and the calculated velocity, V , is in feet per second. The discharge per unit width q can then be computed according to the following equation:

$$q = (V_o \Delta n_o)N \tag{11}$$

where N = the number of spaces between the streamlines. The total discharge

$$Q = qL \tag{12}$$

where L is the effective length of the spillway. The effective length of the spillway crest is reduced by contractions around the piers (Figure 13). In this case, only one bay was operating, so the adjacent bays were treated as abutments. HDC Sheet 111-3/1 was used to compute an effective crest length of 45.83 ft for the 50-ft-wide bay. The discharge was thus computed to be 36,397 cfs for test 7. However, since the electric analog solution assumes potential flow, an adjustment for

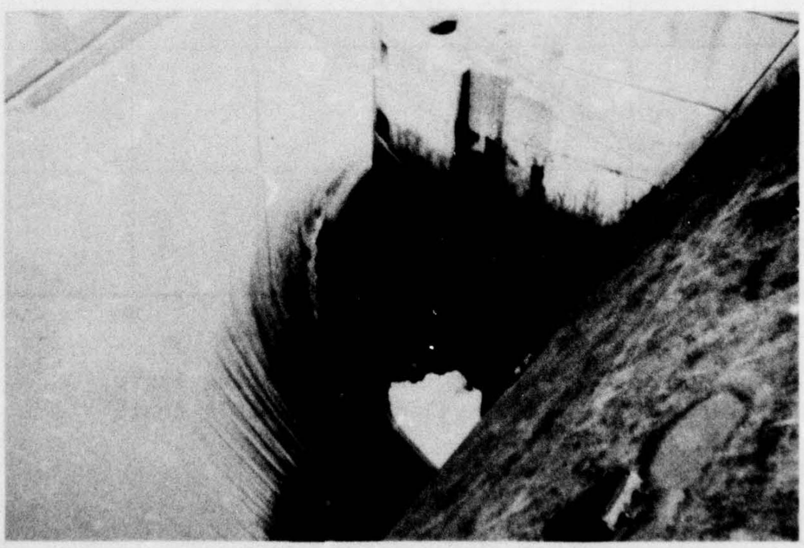

Figure 13. Contraction around spillway pier during free flow

friction losses needs to be introduced. Figure 14 is a comparison of measured velocities and velocities computed from the flow net; the measured velocities are about 8 percent less at all three probes. The surface velocity measured with the optical flowmeter at the center of spillway bay 8 (20 fps) was also less than the flow net velocity at that point (23.26 fps). Consequently, the computed discharge was reduced by 8 percent to 33,485 cfs.

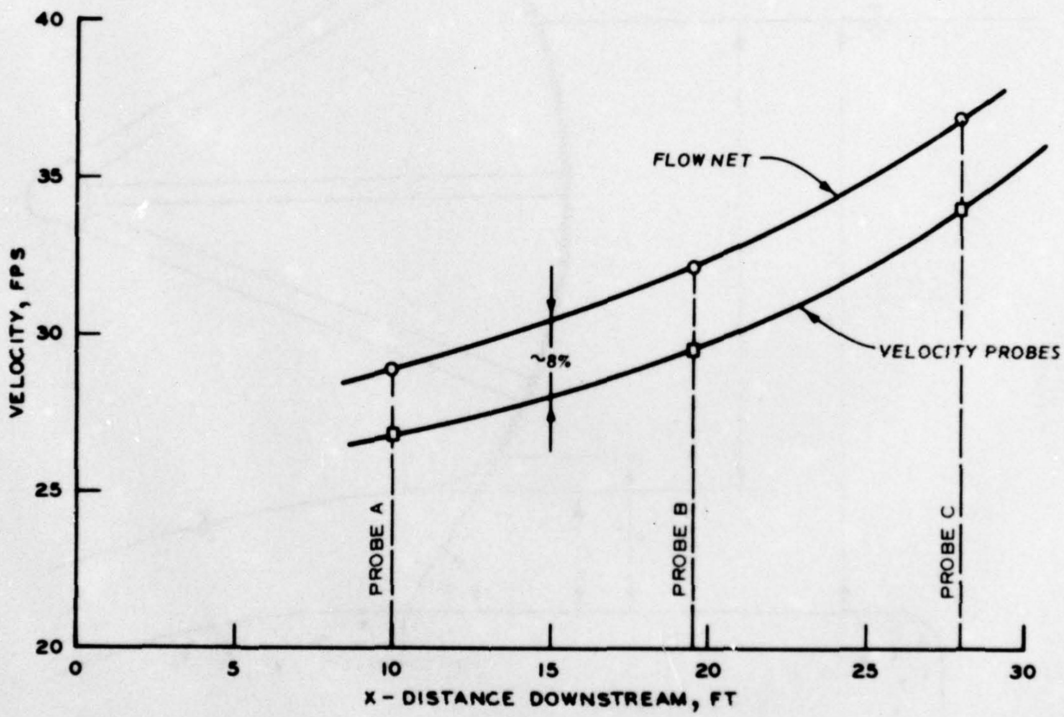

Figure 14. Comparison of velocities computed by electric analog with measured velocities

Partial gate openings

29. Figure 15 is a definition sketch for partial gate opening flow conditions. Assuming potential flow, the discharge is computed according to the following equation.

$$Q = A\sqrt{2gh} \qquad (13)$$

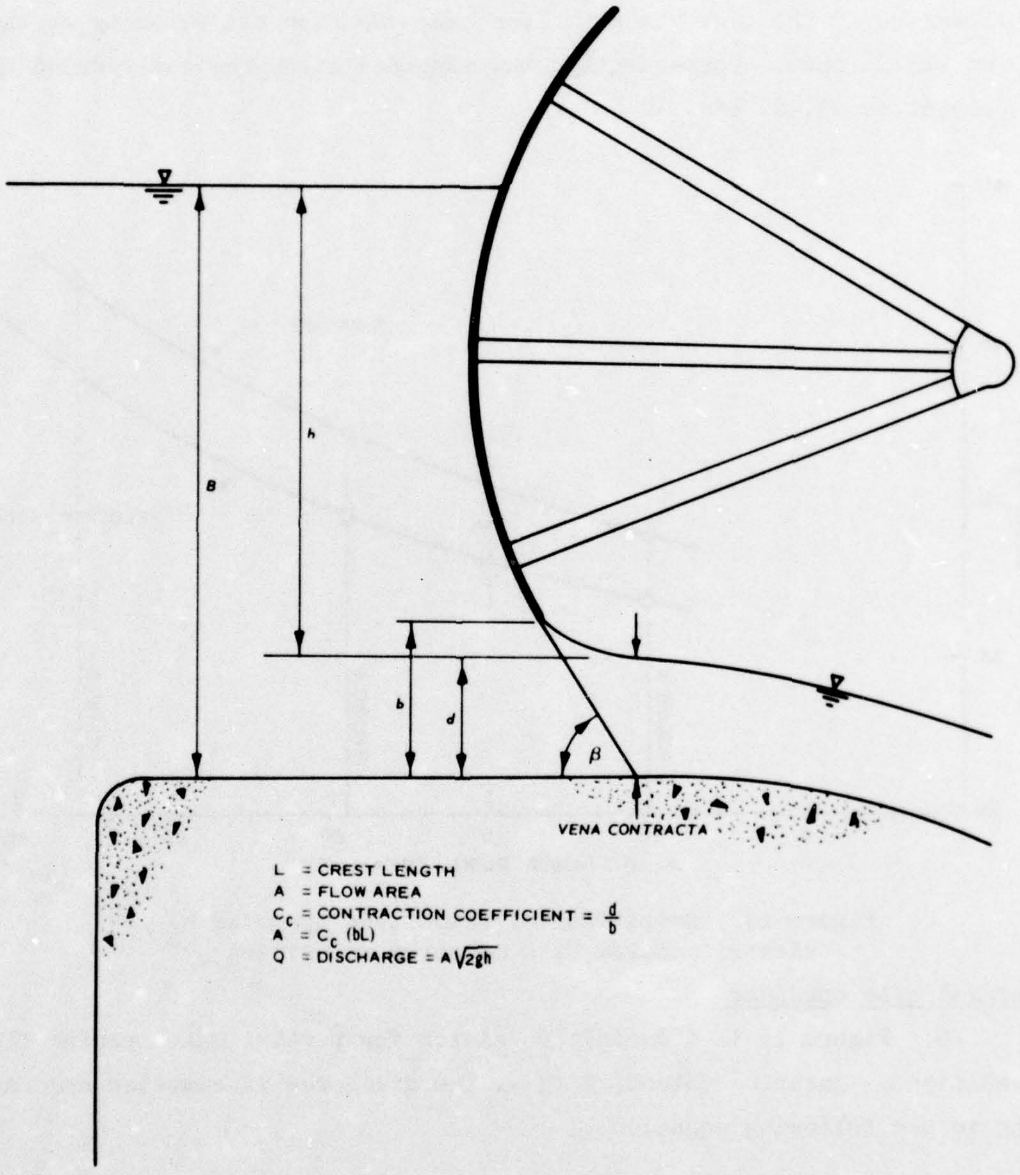

Figure 15. Definition sketch for partial gate opening flow conditions

30. The contraction coefficient C_c is needed for each gate opening to determine Q. Von Mises[10] collected contraction coefficient data for various angles of convergence β and gate opening versus head ratios b/B. These data were used to develop the family of curves shown in Plate 10. The angle of convergence for Ozark was then determined for and plotted on each Von Mises b/B curve. Connecting these points results in a curve specifically for Ozark ($B = 41.7$ ft) relating β to C_c. The contraction coefficients for each gate opening from Plate 10 were used in equation 13 to determine discharge. These discharges were also reduced by 8 percent to account for friction losses.

Pressure on Spillway Face

31. The average and maximum fluctuating pressures measured on transducers A, B, and C are given in Table 2 and plotted in Plate 11. The magnitude of the boundary layer fluctuations was relatively small and probably would not cause any structural vibrations. Time-history plots of the baseline noise data and data during a typical test (gate open 8 ft) on pressure transducer B are given in Plate 12. Fourier transform plots in the frequency domain for the time series data are also given in Plate 12. The frequency peak at 2.7 cps in the baseline test is probably the natural frequency of the structure since it occurs on all channels (except the gate accelerometer channels) during all tests. The frequency peak at 1.17 cps does not appear in the baseline noise test, so it is attributed to the boundary layer pressure fluctuations.

Vibrations

32. Maximum spillway and gate vibrations are listed in Table 3. Actual spillway vibrations were very small. The signal-to-noise ratio was less than 2 for accelerometers 1 through 5 and about 6 for accelerometers 6 and 7. The large noise and small signal levels precludes detailed comparisons between accelerometers located on the

structure (to determine details of the motion of the monolith). Plate 13 is a typical set of acceleration versus time and acceleration versus frequency plots for accelerometer 4H. The frequency peak at 16.4 cps is probably associated with the natural frequency of the pier since it appears in the noise test as well as in the 8-ft gate opening test. The peak at 60 cps was attributed to equipment noise. Plate 14 is a set of acceleration versus time and acceleration versus frequency plots for gate accelerometer 6R. There are several dominant frequencies from 8 to 24 cps in the frequency domain test plot. However, the magnitude of the vibrations was not large enough to be of concern.

33. The four 0- to 2-sec correlograms shown in Plate 15 tend to substantiate the observations above regarding the spikes in the frequency domain plots. The only 0- to 0.2-sec correlogram that may demonstrate a cause-and-effect relationship concerns the correlation between pressure cell B and accelerometer 6R. This plot indicates that those pressure fluctuations occurring near 8 cps precede the corresponding gate acceleration by about 0.03 sec.

34. The frequency domain graphs and correlograms in Plates 12-15 were computed and plotted from data digitized from the Ozark magnetic tape records. The Fast Fourier Transform computer program used in the analysis was adapted by the Data Reduction Section at WES for the EAI 640 computer from a program written at the National Research Council in Ottawa, Canada.

35. The following tabulation indicates that the ranges obtained from the oscillographs (Tables 2 and 3) may overestimate the actual fluctuations by factors in the order of 6 to 17 for transducers 1V, 2V, 3H, 4H, and 5V; in the order of 2.8 to 3.4 for 6R and 7T; and in the order of 2.5 to 3.0 for A, B, and C. Data from the oscillograph records and the data comprising the digital samples are expected not to be identical because of the statistical nature of discrete sampling and because of the relatively large noise level (light-beam width) on the oscillograph charts. The comparison (R_1/R_2 in the tabulation) indicates that the extreme amplitudes obtained from the oscillograph charts are

invalid for transducers 1V, 2V, 3H, 4H, and 5V due probably to high noise levels; on the other hand, the smaller differences for the rest of the transducers may be due more to the shortness of the digital record and discrete sampling than to scaling the oscillograph charts.

Transducer	Units	Max Data Range (Peak-to-Peak) Oscillograph, R_1	Max Data Range (Peak-to-Peak) 5.12-sec Sample, R_2	RMS 5.12-sec Sample	R_1/R_2
1V	g's	0.076	0.0045	0.00070	17
2V	g's	0.022	0.0033	0.00060	7
3H	g's	0.020	0.0020	0.00033	10
4H	g's	0.018	0.0032	0.00052	6
5V	g's	0.074	0.0048	0.00081	15
6R	g's	0.063	0.0223	0.00335	2.8
7T	g's	0.061	0.0180	0.00251	3.4
A	ft	0.81	0.282	0.0412	2.9
B	ft	1.82	0.600	0.104	3.0
C	ft	3.27	1.299	0.235	2.5

Other Observations

36. A great deal of sand passed through the spillways at Ozark. The abrasive action of the sand severely damaged the velocity probe assemblies (Figure 16). Many of the tubes were broken from the assemblies during the tests and the probe housing was pitted. Most of the readings were still valid, however, because the pressure lines remained open and the openings on the front of the probes continued to sense the stagnation pressure. The concrete on the spillway sill was also observed to be severely eroded by the sand.

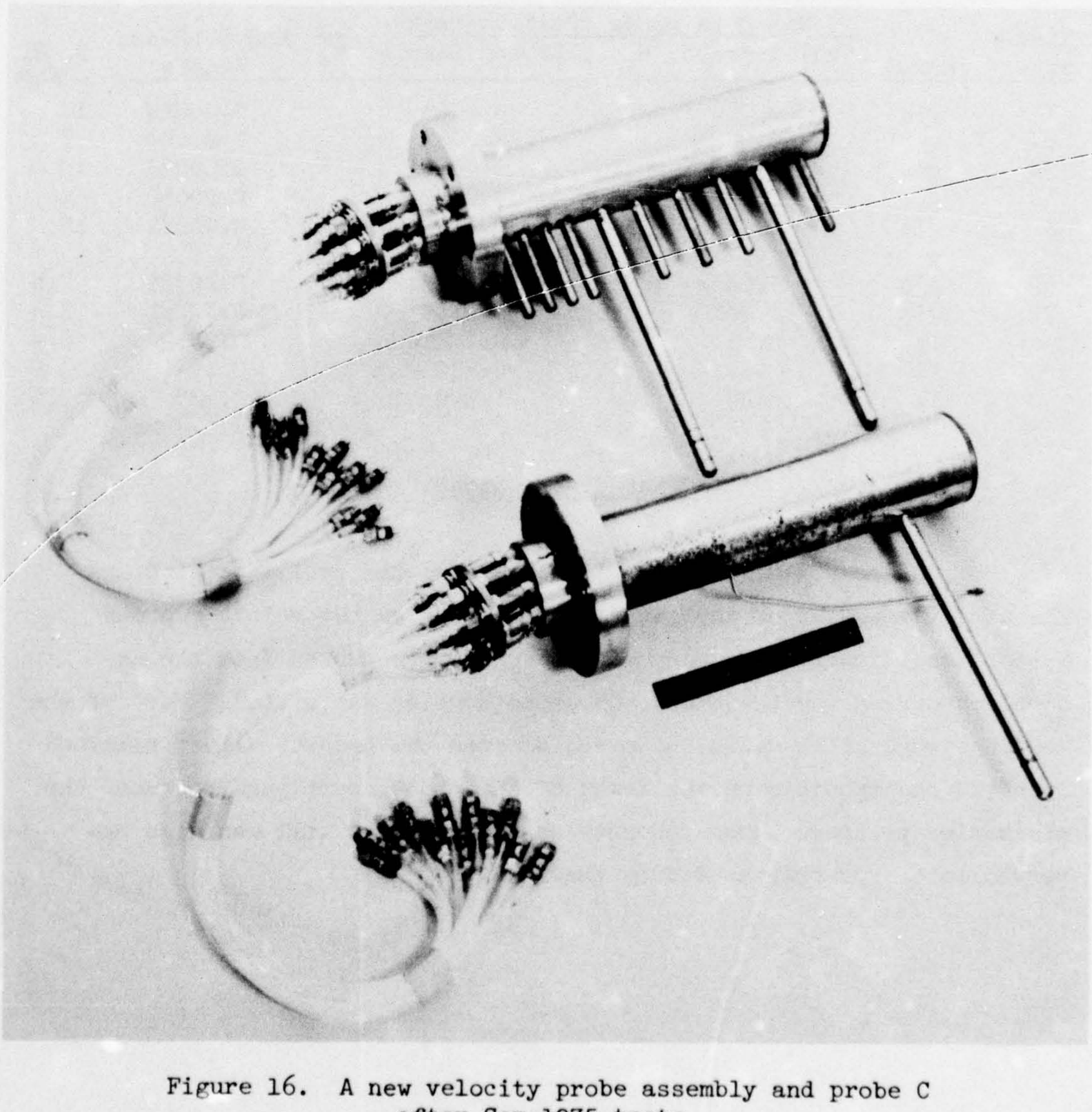

Figure 16. A new velocity probe assembly and probe C after Sep 1975 tests

PART V: CONCLUSIONS

37. The following conclusions resulted from analysis of the test data:

a. Pressure fluctuations on the low overflow spillway crest did not exhibit an unusually high RMS value. A peak appeared in the frequency domain plot at 1.17 cps. However, the magnitude of the fluctuations was not considered large enough to be a source of excitation of spillway vibration.

b. The structure appeared to be vibrating at a natural frequency of 2.7 cps.

c. Vibrations of the structure and the gate were relatively small. The gate did not exhibit any tendencies to vibrate more at small gate openings than at large gate openings.

d. The equivalent sand grain roughness K_s determined for the Ozark spillway (0.0061 ft) supplements the data determined at other projects with concrete surfaces.

e. The theoretical boundary layer thickness δ computed according to the following equation

$$\delta = X \frac{0.377}{R_x^{1/5}} \qquad (1)$$

is generally confirmed by the velocity profile plots.

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2. Locher, F. A., "Some Characteristics of Pressure Fluctuations on Low-Ogee Crest Spillways Relevant to Flow-Induced Structural Vibrations," Contract Report H-71-1, Feb 1971, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.; prepared by Iowa Institute of Hydraulic Research, University of Iowa, under Contract No. DACW39-68-C-004.

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Table 1

Velocity Profiles, in fps, at Probes A, B, and C, Tests 1-7

Distance from Spillway ft	Probe A	Probe B	Probe C	Probe A	Probe B	Probe C	Probe A	Probe B	Probe C
		Test 1			Test 2			Test 3	
0.9375	20.21	20.70	27.81	22.75	27.44	32.08	14.27	23.51	23.65
0.8125	20.17	20.74	28.00	22.69	27.44	31.96	13.81	23.65	23.31
0.6875	20.17	20.55	27.86	22.69	27.66	32.11	14.04	23.58	23.50
0.5625	20.17	20.55	27.97	22.69	27.63	32.16	13.81	23.58	23.36
0.4375	20.09	20.52	28.00	22.69	27.63	31.49	13.81	23.58	22.39
0.3333	20.58	20.29	28.05	22.62	*	32.59	13.70	*	22.67
0.2292	20.17	20.55	27.86	22.59	27.63	32.11	12.34	23.17	23.50
0.1667	20.09	20.63	27.59	22.52	27.63	32.38	12.85	22.96	20.84
0.1042	20.09	20.55	27.94	22.49	27.55	31.39	12.34	22.68	19.41
0.0417	20.13	20.48	28.24	22.21	27.27	6.25	11.53	19.96	2.50
		Test 4			Test 5			Test 6	
0.9375	24.37	32.10	39.28	27.52	34.09	38.19	22.95	29.78	36.25
0.8125	24.42	32.15	39.40	27.52	34.08	38.19	24.55	29.78	36.50
0.6875	24.38	32.14	39.16	27.52	34.08	38.32	24.55	29.66	36.50
0.5625	24.38	32.15	39.40	27.52	34.09	38.40	24.77	29.60	36.60
0.4375	24.40	32.15	39.40	27.29	34.09	38.73	24.47	29.78	36.74
0.3333	24.33	*	36.59	27.41	*	*	23.88	*	*
0.2292	24.24	32.10	39.20	27.32	34.01	38.85	24.40	28.67	35.55
0.1667	24.27	32.09	37.70	27.28	33.98	34.89	23.80	28.04	35.65
0.1042	24.20	31.82	35.93	27.06	33.63	*	20.81	26.18	*
0.0417	23.90	30.95	30.50	26.81	32.74	30.12	18.03	21.32	28.45
		Test 7							
0.9375	24.70	29.46	33.00						
0.8125	26.84	29.46	34.12						
0.6875	26.84	29.22	34.07						
0.5625	26.77	29.34	34.07						
0.4375	26.70	28.97	33.86						
0.3333	26.16	*	*						
0.2292	24.89	27.37	32.11						
0.1667	23.62	26.97	29.84						
0.1042	21.13	*	*						
0.0417	17.79	17.69	24.90						

* Piezometer line clogged.

Table 2

Average and Maximum Fluctuating Pressures,

Pressure Cells A, B, and C,

Tests 10-21

	Pressure-ft of Water					
	Pressure Cell A		Pressure Cell B		Pressure Cell C	
Test No.	Avg*	Max Fluc	Avg	Max Fluc	Avg	Max Fluc
10	42.94	±0.37	42.48	±0.43	38.10	±0.31
11	42.77	±0.33	41.72	±0.47	38.81	±0.31
12	42.12	±0.41	38.92	±0.43	36.15	±0.36
13	40.48	±0.62	33.67	±0.72	34.02	±0.45
14	38.68	±0.81	30.95	±1.82	10.45	±3.27
15	36.92	±0.81	27.91	±1.52	9.15	±3.27
16	33.54	±0.97	24.27	±1.22	11.11	±2.62
17	32.26	±0.64	23.97	±1.52	11.11	±3.60
18	30.33	±0.56	22.76	±1.22	9.80	±2.29
19	28.73	±0.64	21.24	±1.67	9.80	±2.29
20	23.75	±1.13	15.17	±2.13	13.07	±3.27
21	16.85	±0.97	10.62	+1.37	13.07	±2.62

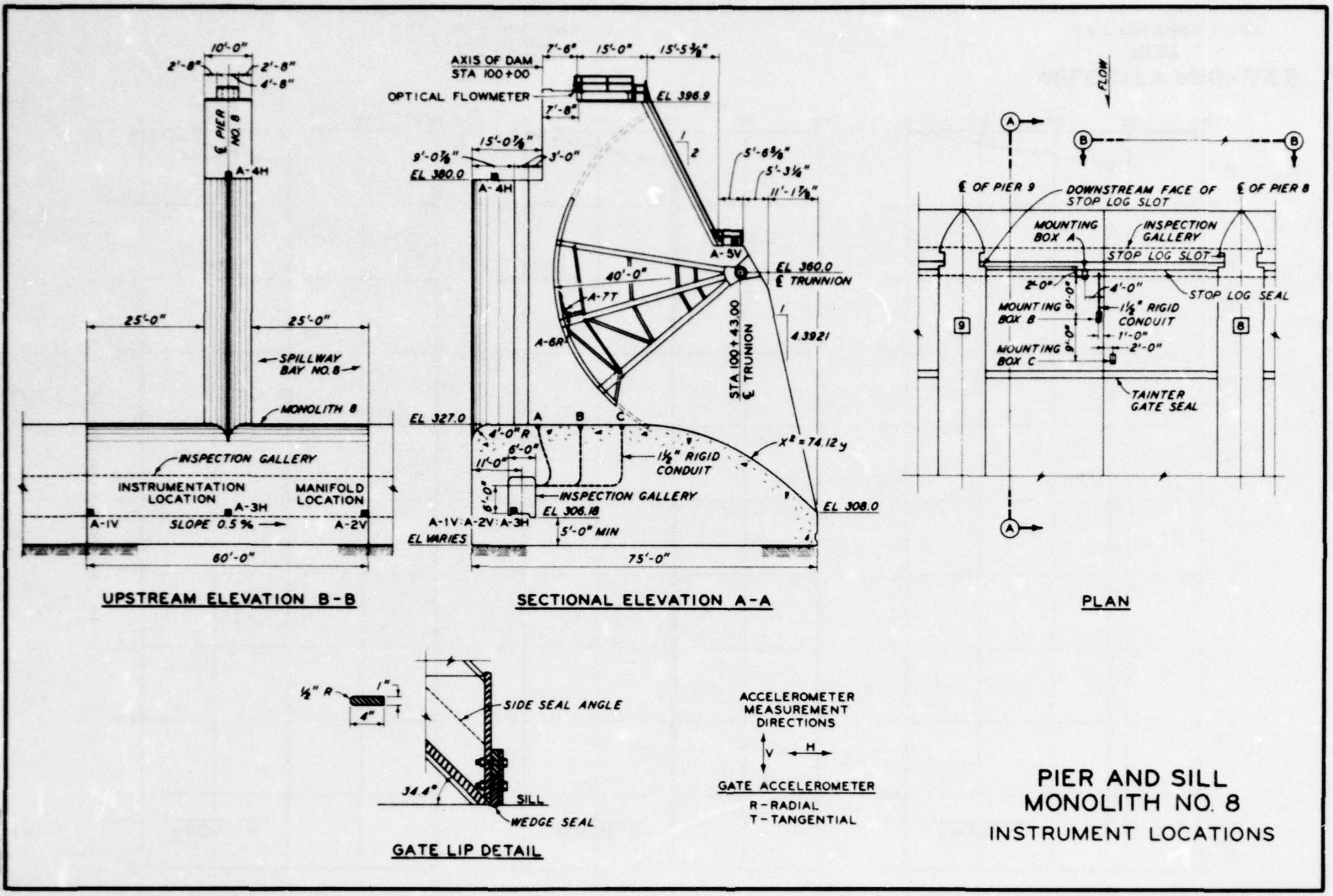
* Average pressure on spillway crest (el 327.0).

Table 3

Pressure Fluctuations and Accelerations

Test No.	Gate Opening ft	Maximum Acceleration in g's 1V	2V	3H	4H	5V	6R	7T
		Gate Stationary (Tests 10-21)						
10		0.070	0.022	0.022	0.015	0.074	0.041	0.072
11	2	0.088	0.035	0.029	0.013	0.062	0.044	0.044
12	4	0.070	0.025	0.022	0.015	0.080	0.041	0.055
13	6	0.088	0.032	0.022	0.018	0.043	0.100	0.072
14	8	0.076	0.022	0.020	0.018	0.074	0.063	0.061
15	10	0.088	0.028	0.027	0.020	0.068	0.037	0.061
16	15	0.070	0.032	0.025	0.015	0.062	0.041	0.066
17	*	0.076	0.028	0.025	0.016	0.062	0.055	0.072
18	20	0.088	0.028	0.024	0.021	0.055	0.037	0.061
19	25	0.082	0.035	0.022	0.021	0.055	0.048	0.055
20	30	0.076	0.032	0.025	0.025	0.062	0.044	0.055
21	34	0.076	0.028	0.022	0.034	0.055	0.052	0.055
		Gate Closing (Test 22)						
22	32	0.088	0.019	0.034	0.039	0.074	0.055	0.072
	30	0.095	0.032	0.025	0.028	0.080	0.063	0.066
	28	0.101	0.032	0.029	0.025	0.080	0.066	0.072
	26	0.095	0.038	0.034	0.025	0.086	0.048	0.083
	24	0.088	0.038	0.029	0.028	0.105	0.059	0.083
	22	0.101	0.028	0.029	0.028	0.099	0.070	0.083
	20	0.107	0.019	0.027	0.023	0.092	0.059	0.077
	18	0.088	0.032	0.034	0.018	0.111	0.077	0.072
	16	0.101	0.025	0.030	0.021	0.099	0.055	0.077
	14	0.095	0.032	0.030	0.018	0.092	0.074	0.083
	12	0.095	0.022	0.027	0.020	0.092	0.074	0.077
	10	0.095	0.028	0.027	0.020	0.105	0.092	0.099
	8	0.095	0.025	0.032	0.021	0.123	0.070	0.094
	6	0.114	0.025	0.029	0.028	0.099	0.059	0.077
	4	0.114	0.025	0.027	0.023	0.099	0.077	0.072
	2	0.095	0.025	0.034	0.020	0.092	0.055	0.094

* Gate opening.



PIER AND SILL
MONOLITH NO. 8
INSTRUMENT LOCATIONS

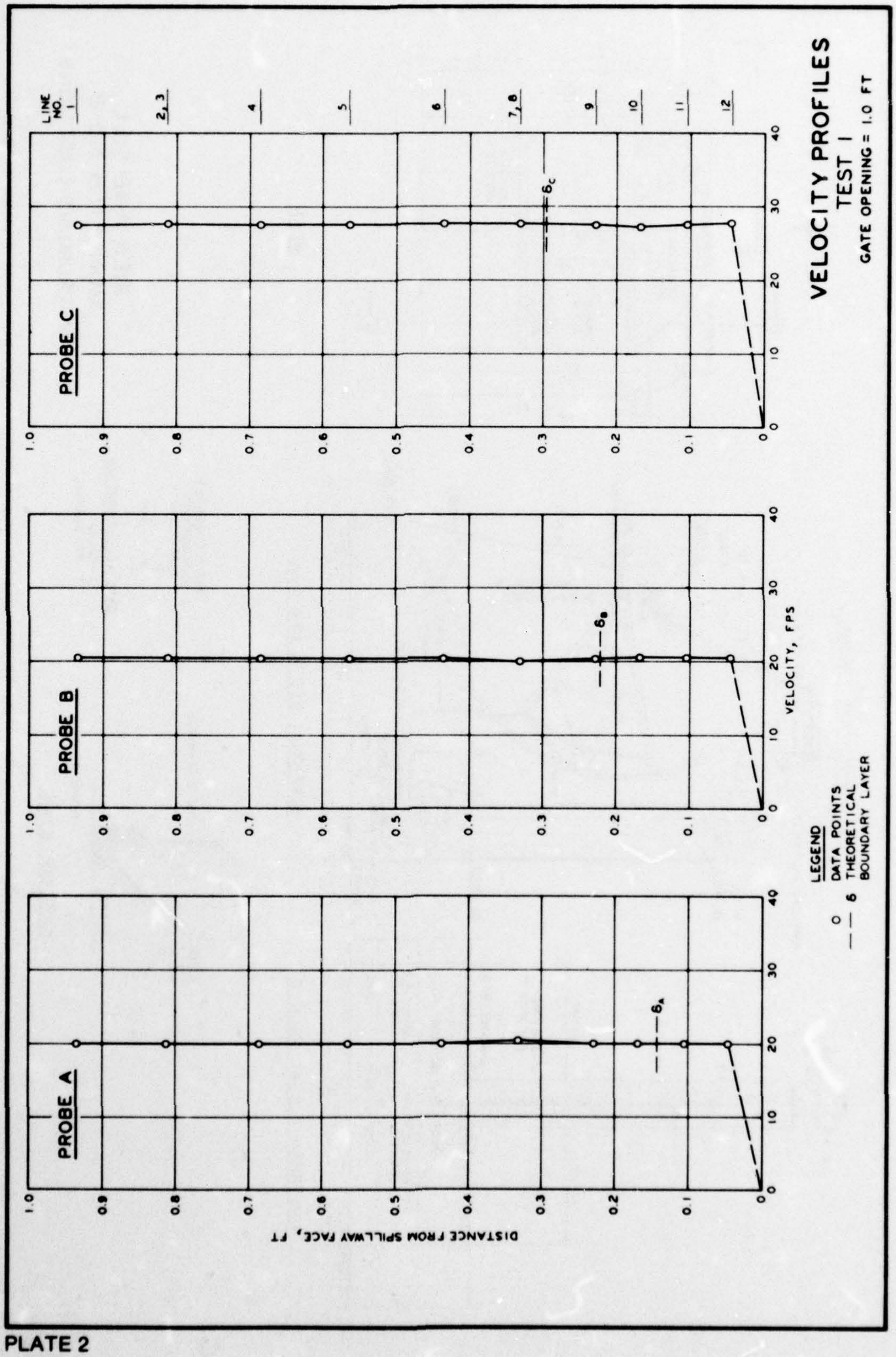
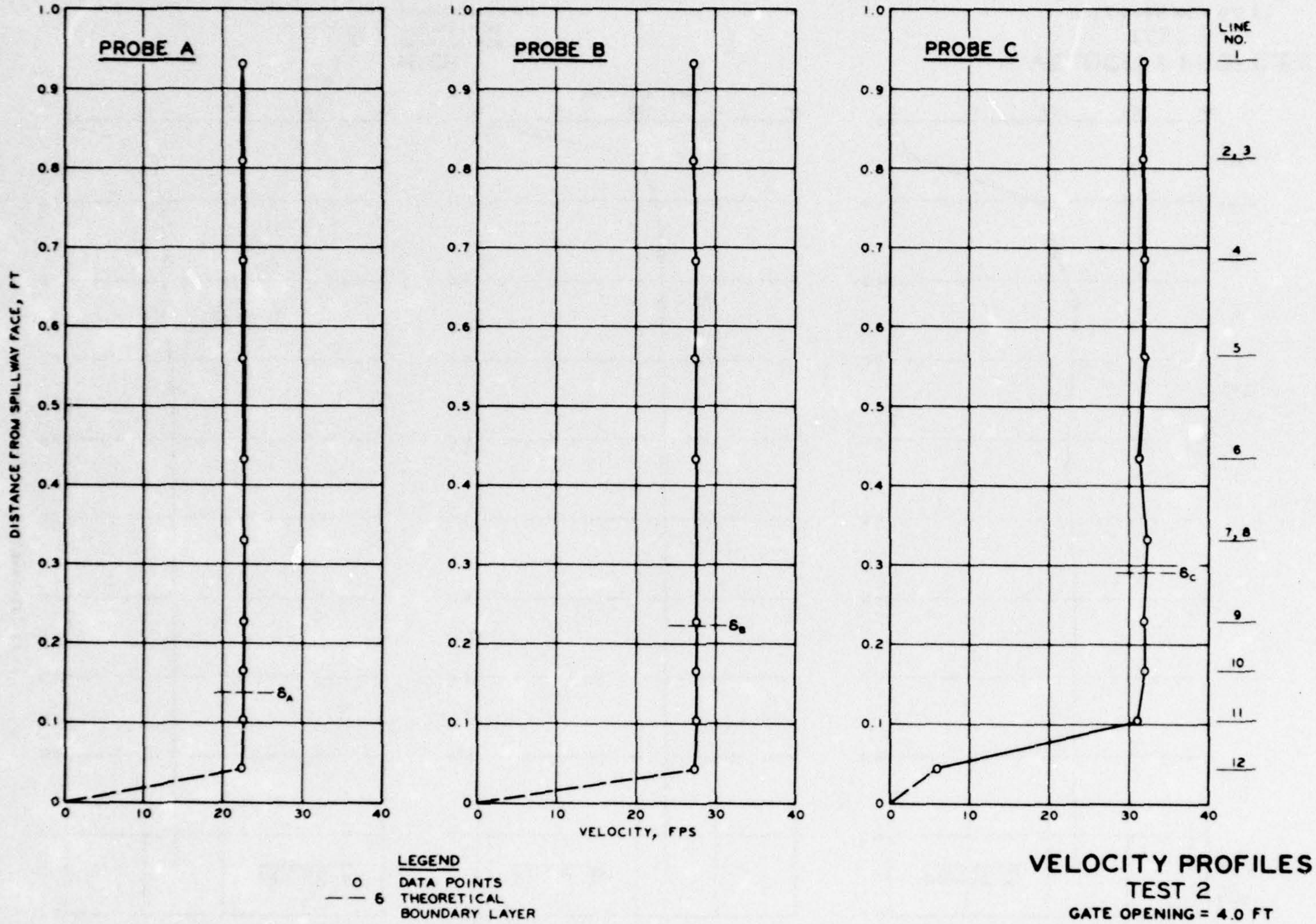
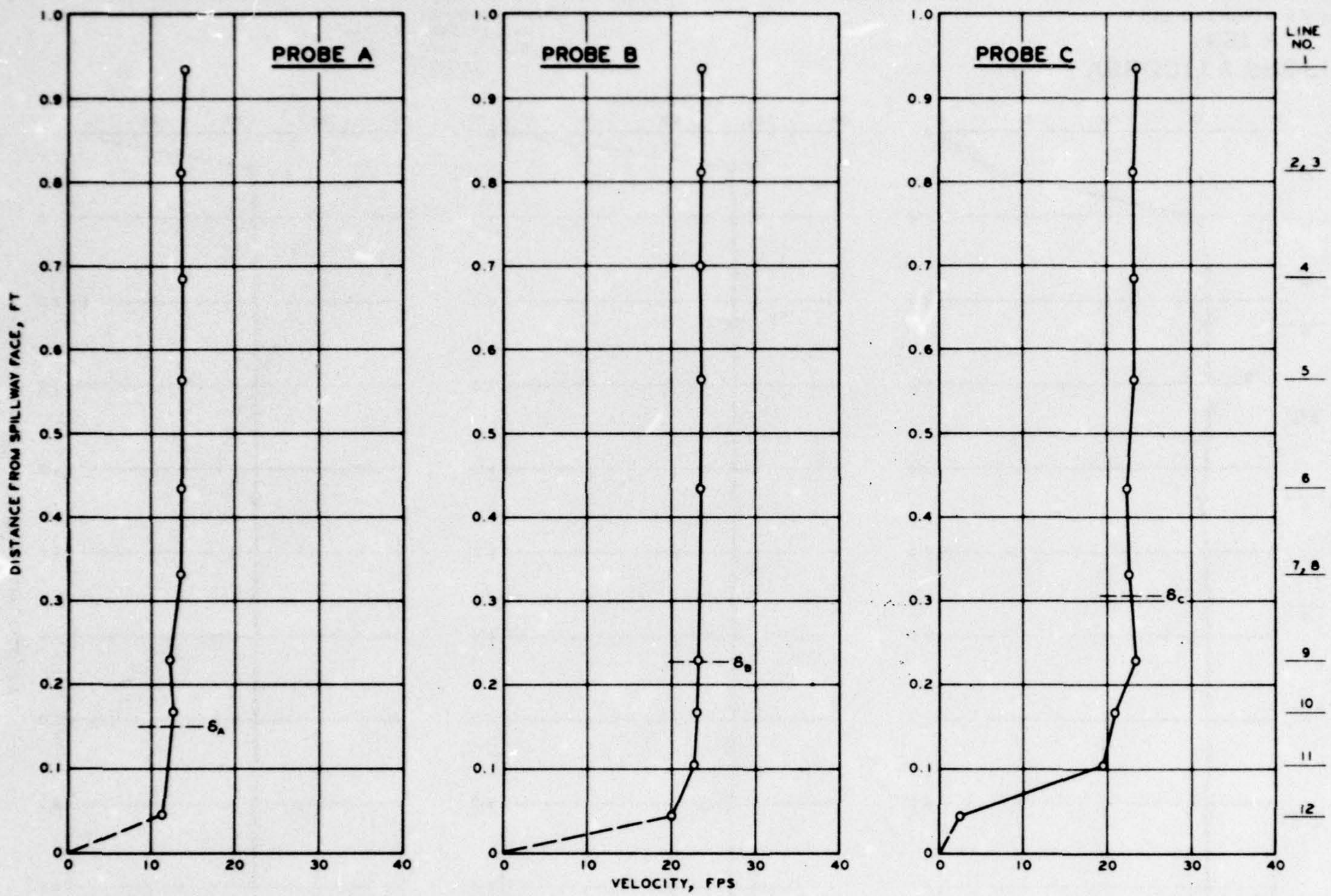

VELOCITY PROFILES
TEST 1
GATE OPENING = 1.0 FT
PROBE A
PROBE B
PROBE C
LINE NO.
DISTANCE FROM SPILLWAY FACE, FT
VELOCITY, FPS
LEGEND
DATA POINTS
THEORETICAL BOUNDARY LAYER

PLATE 2

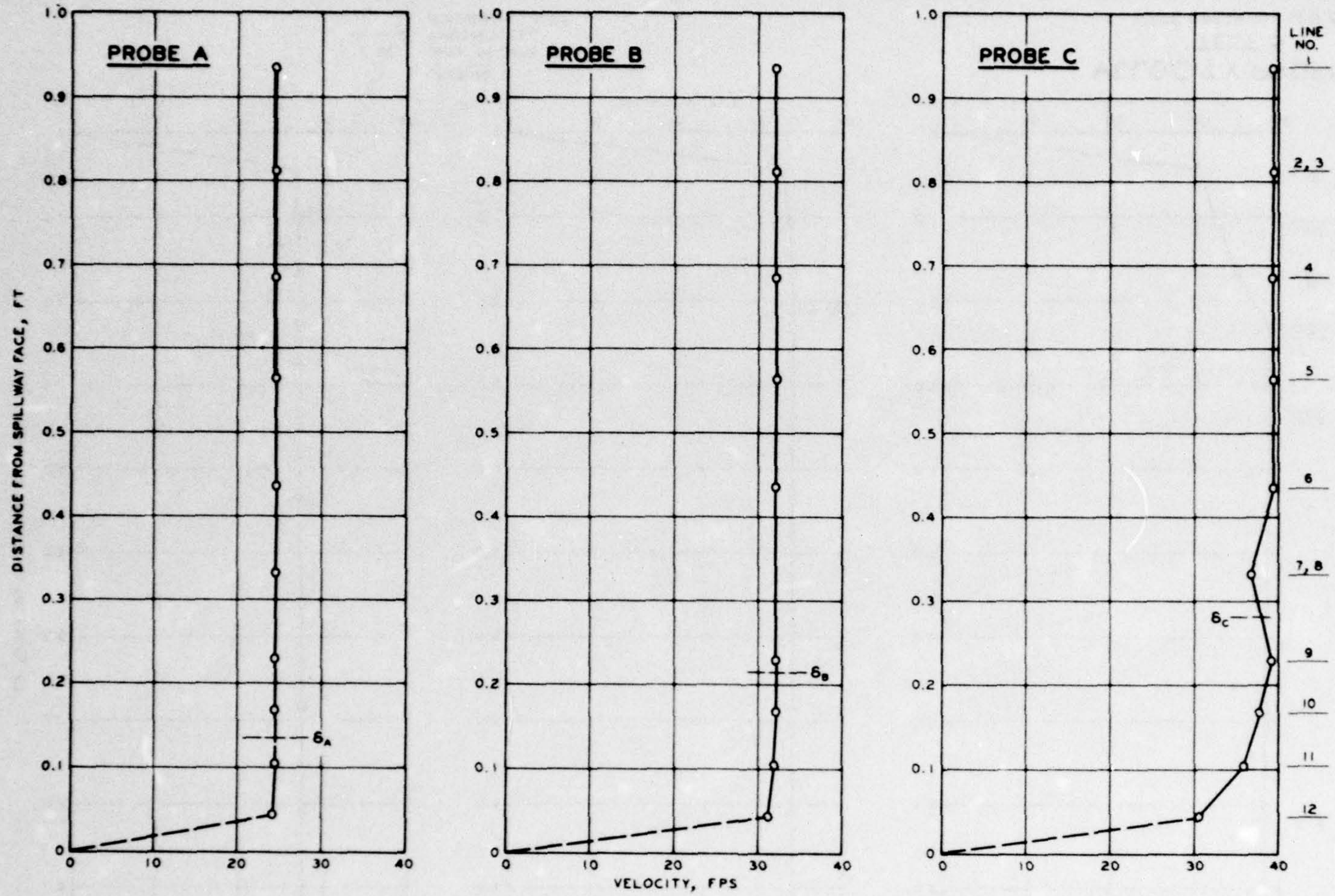


VELOCITY PROFILES
TEST 2
GATE OPENING = 4.0 FT



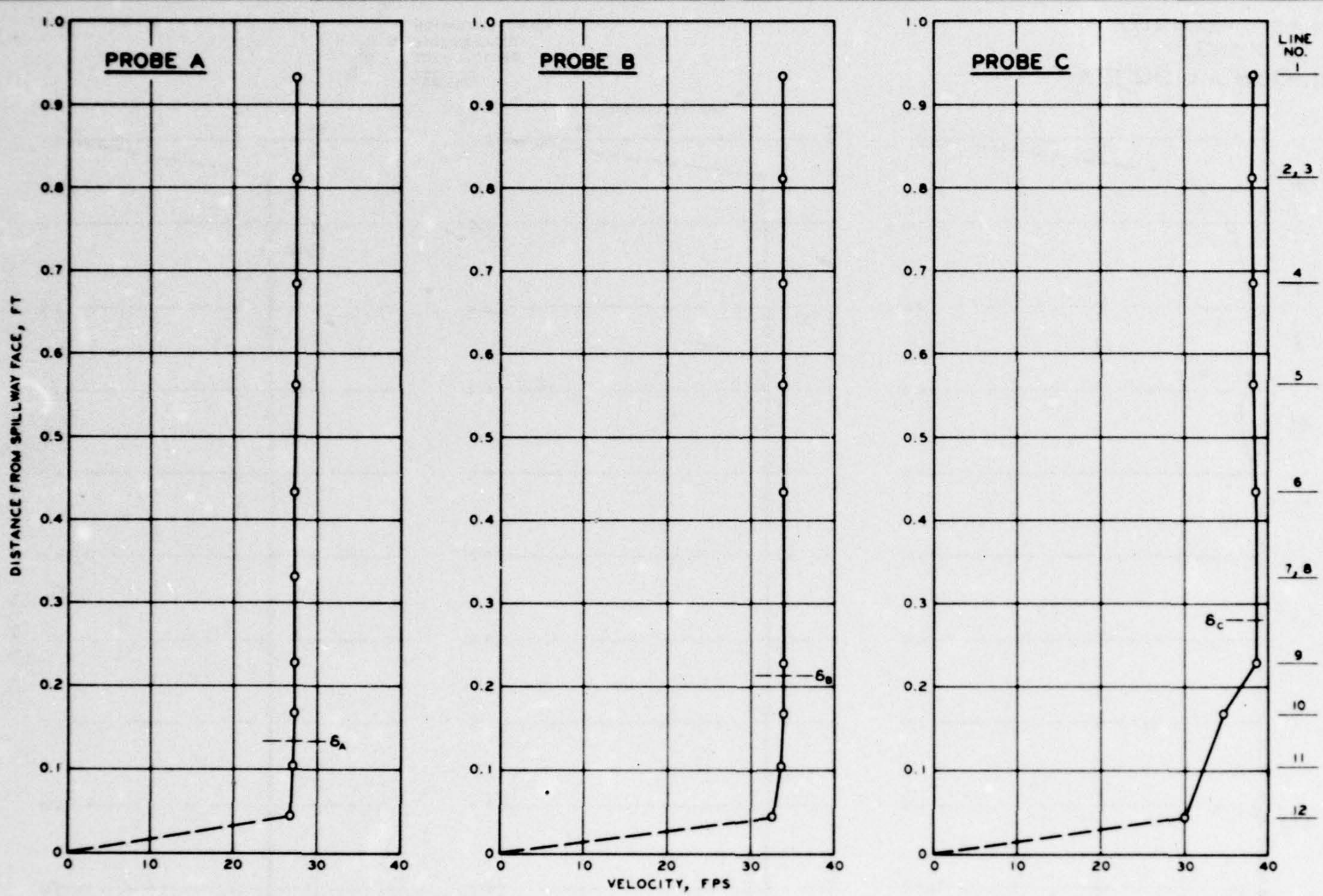
VELOCITY PROFILES
TEST 3
GATE OPENING = 8.0 FT

PLATE 4



LEGEND
o DATA POINTS
— — δ THEORETICAL BOUNDARY LAYER

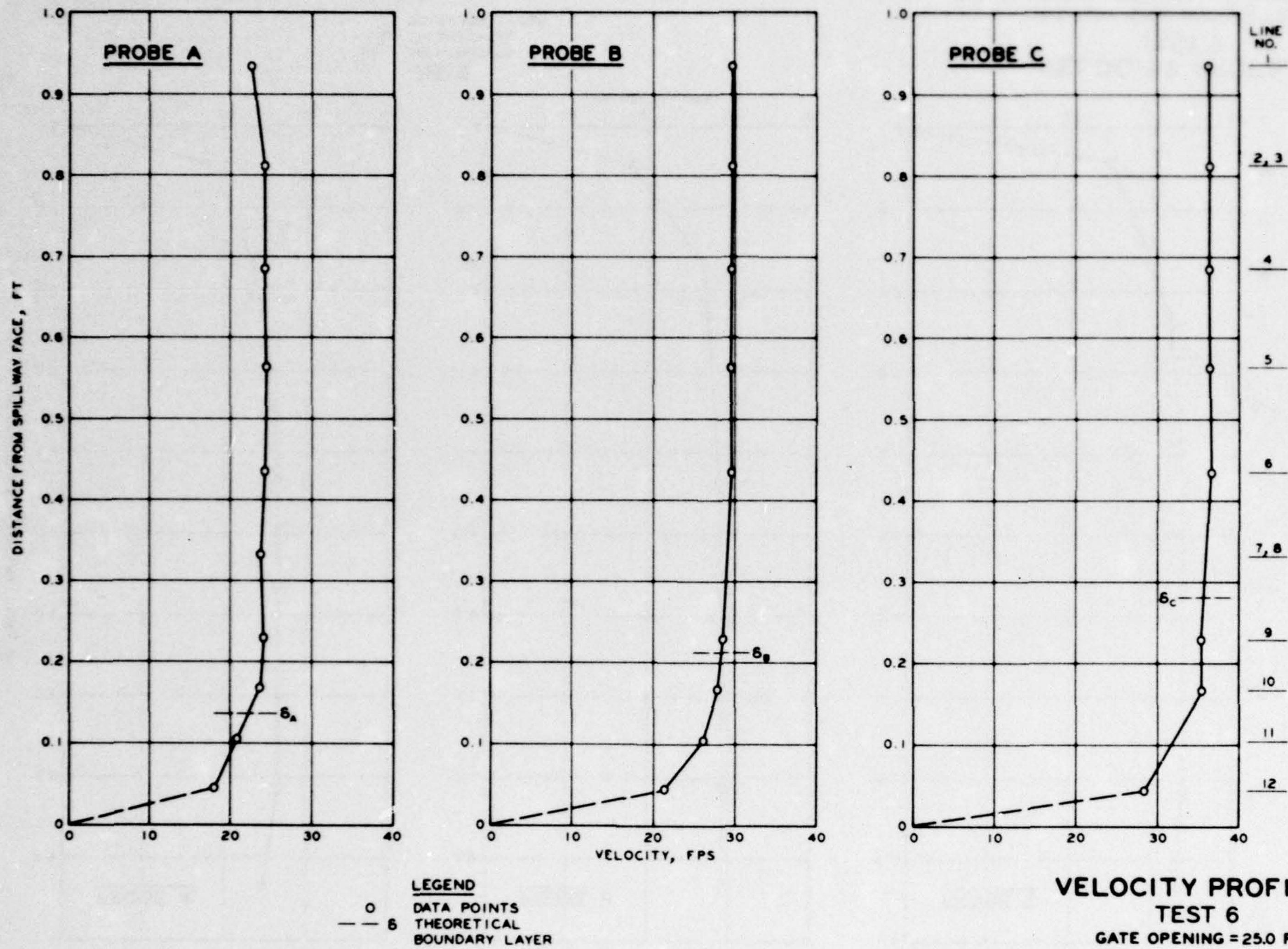
VELOCITY PROFILES
TEST 4
GATE OPENING = 12.0 FT



LEGEND
O DATA POINTS
— — δ THEORETICAL BOUNDARY LAYER

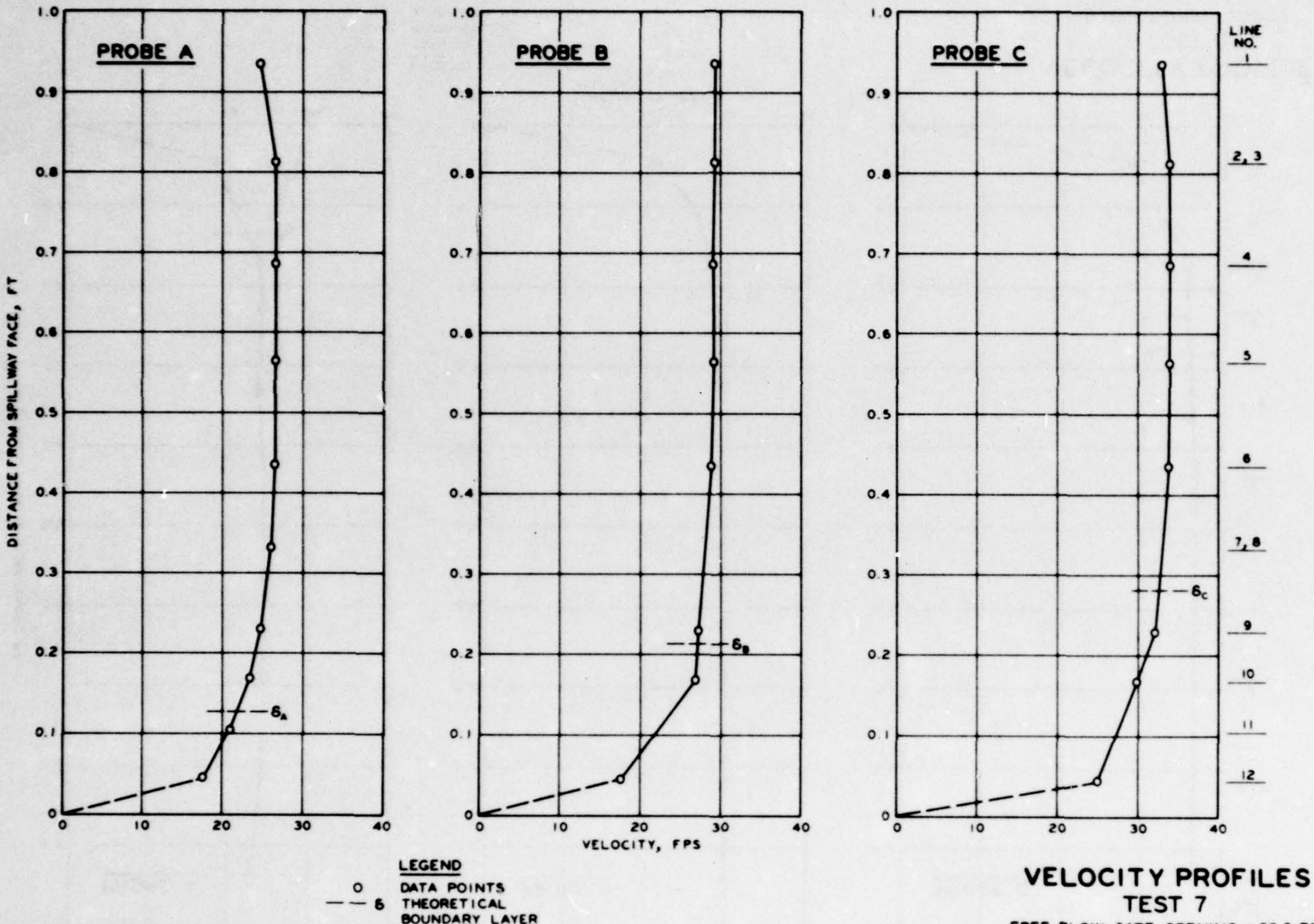
VELOCITY PROFILES
TEST 5
GATE OPENING = 17.0 FT

PLATE 6

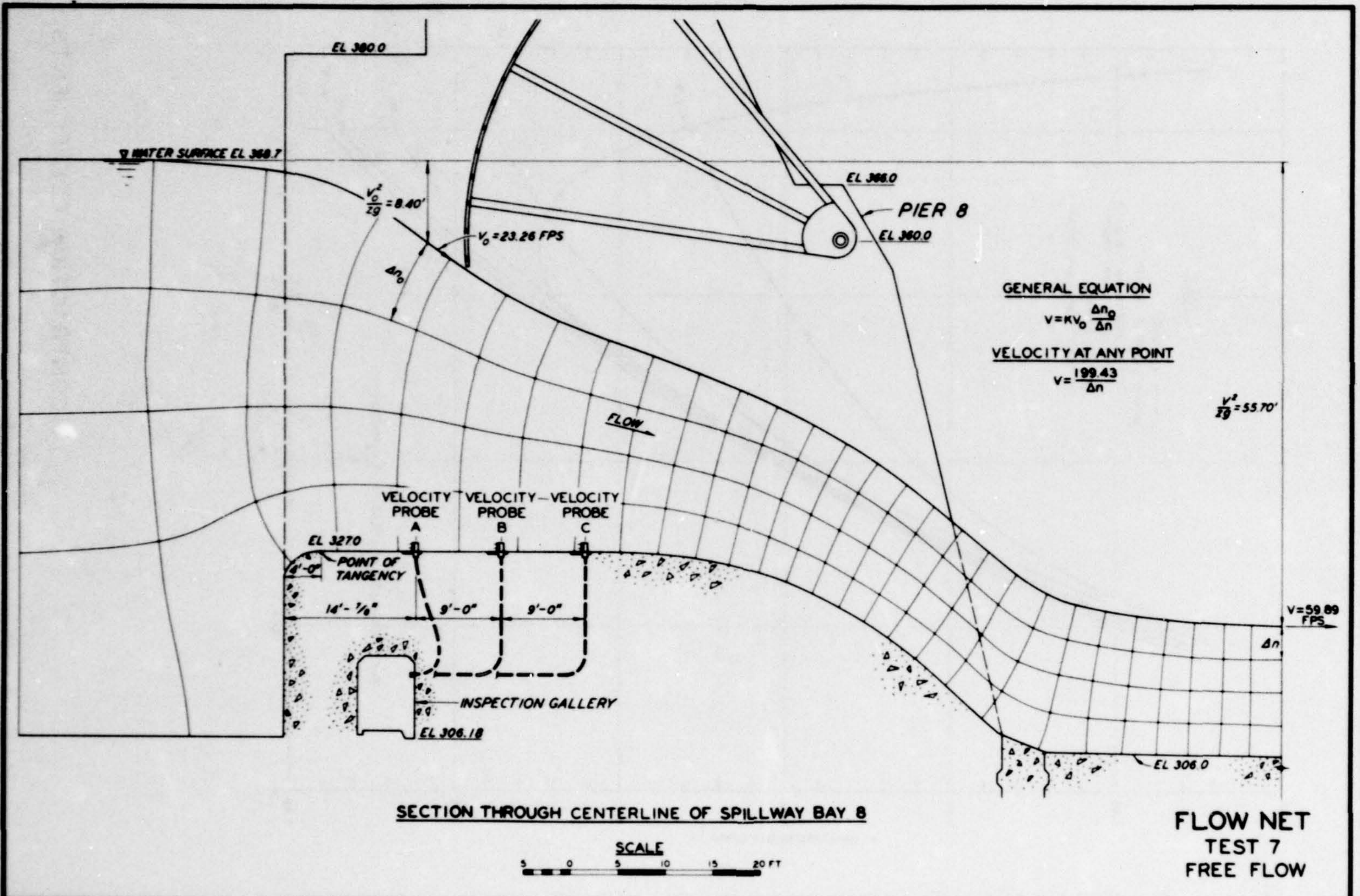


VELOCITY PROFILES
TEST 6
GATE OPENING = 25.0 FT

PLATE 7

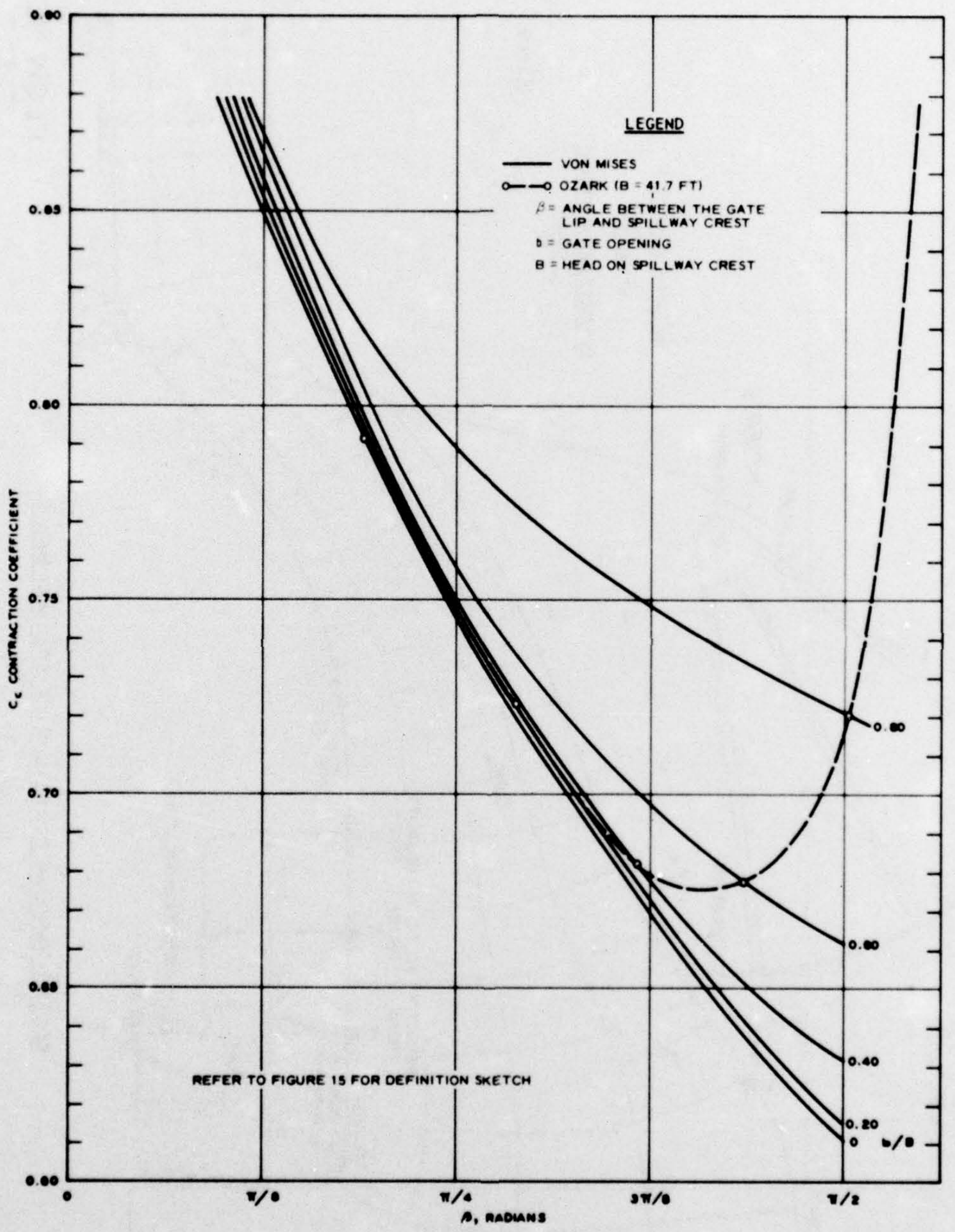


VELOCITY PROFILES
TEST 7
FREE FLOW, GATE OPENING = 32.5 FT

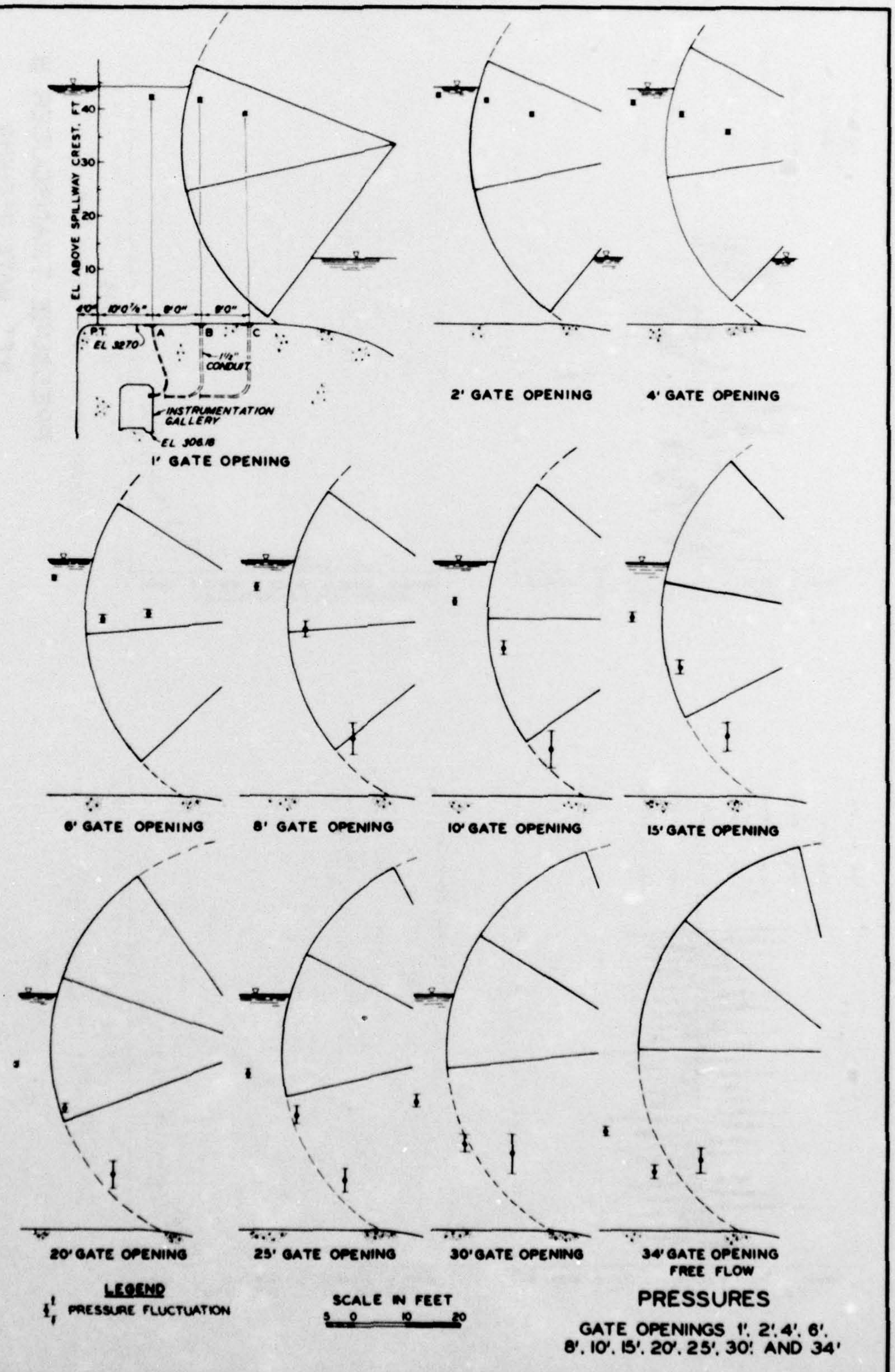


SECTION THROUGH CENTERLINE OF SPILLWAY BAY 8

FLOW NET
TEST 7
FREE FLOW

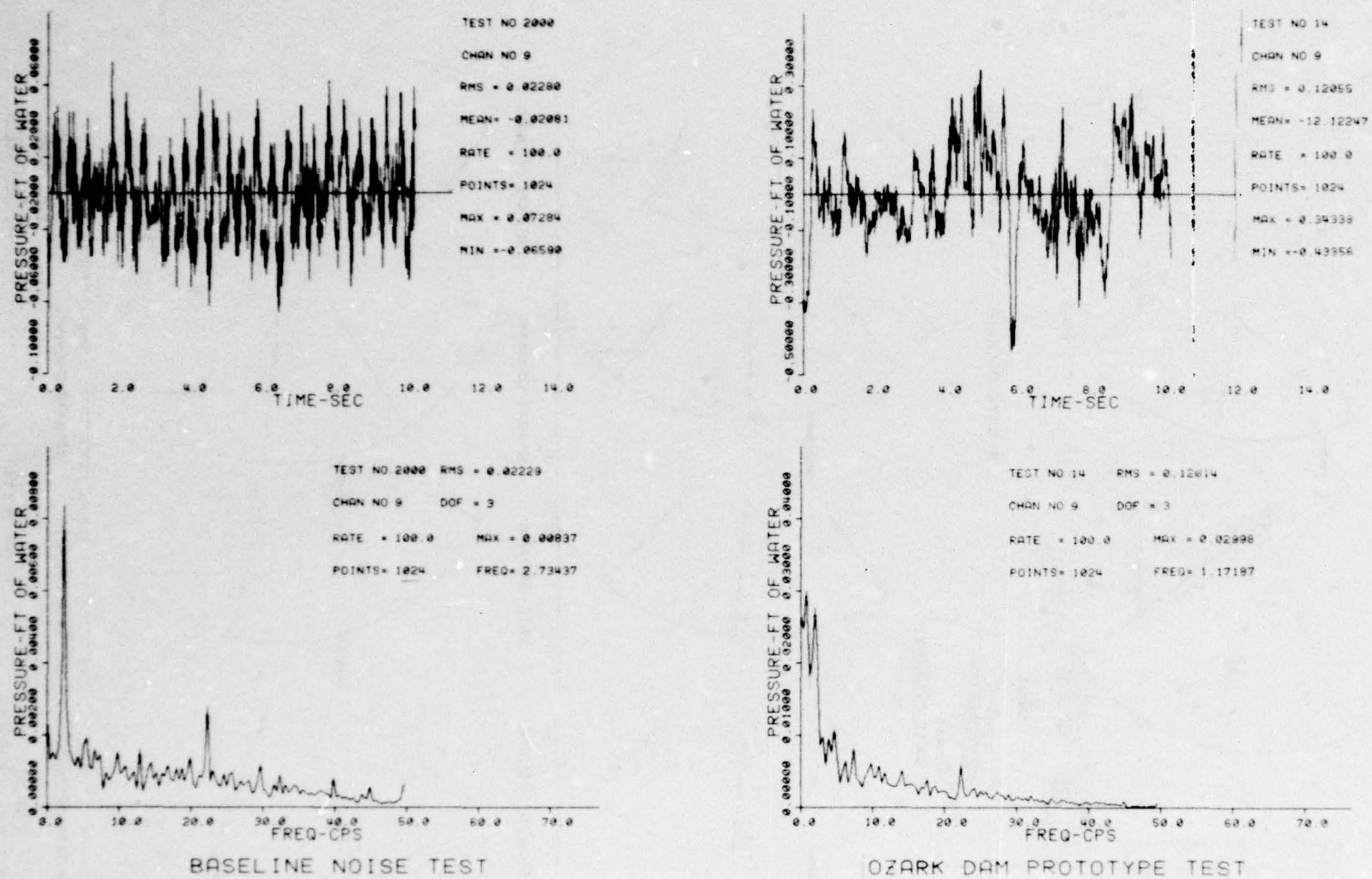


CONTRACTION COEFFICIENTS



PRESSURES

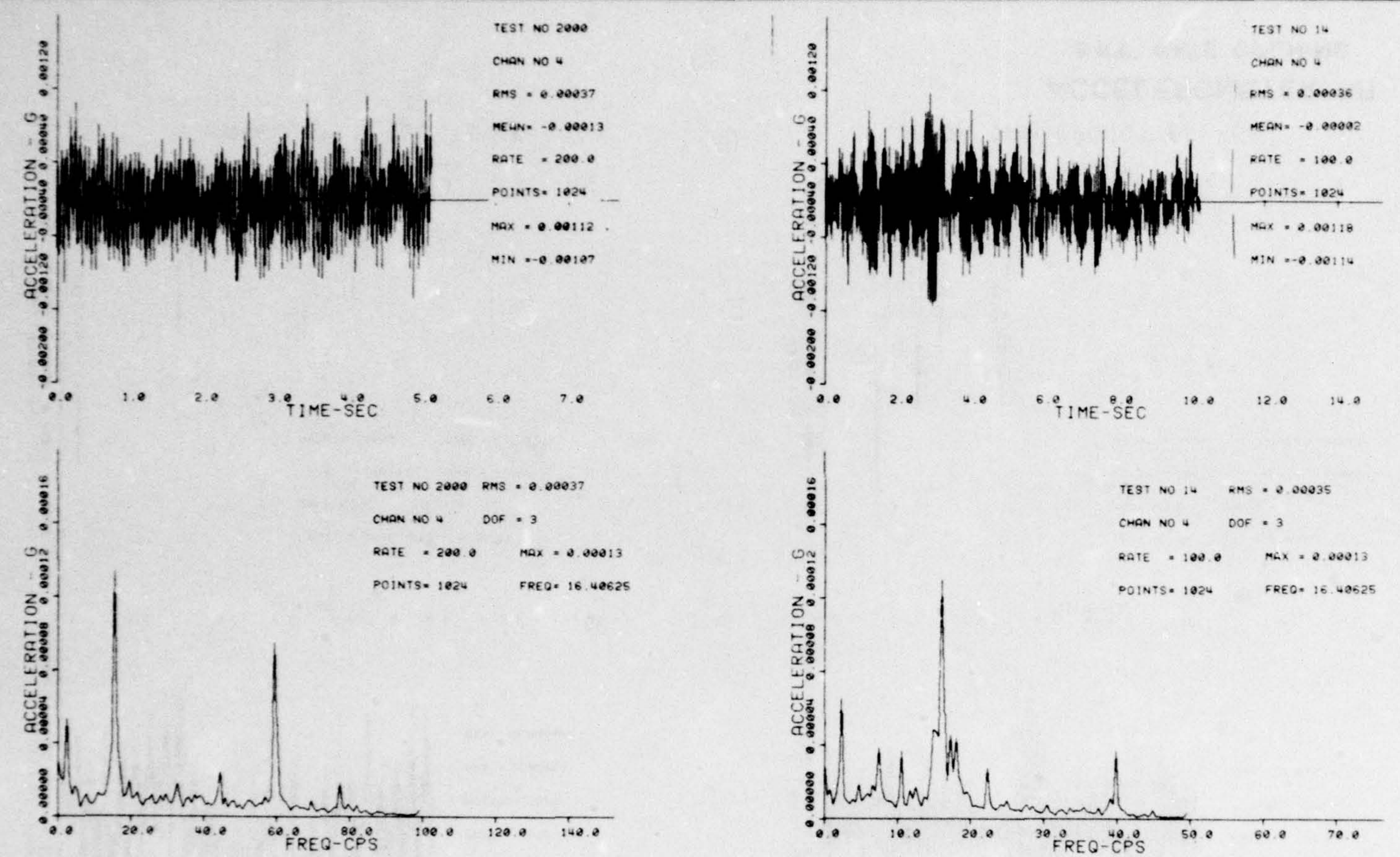
GATE OPENINGS 1', 2', 4', 6', 8', 10', 15', 20', 25', 30', AND 34'



PRESSURE TRANSDUCER B

8-FT GATE OPENING

PLATE 12



BASELINE NOISE TEST

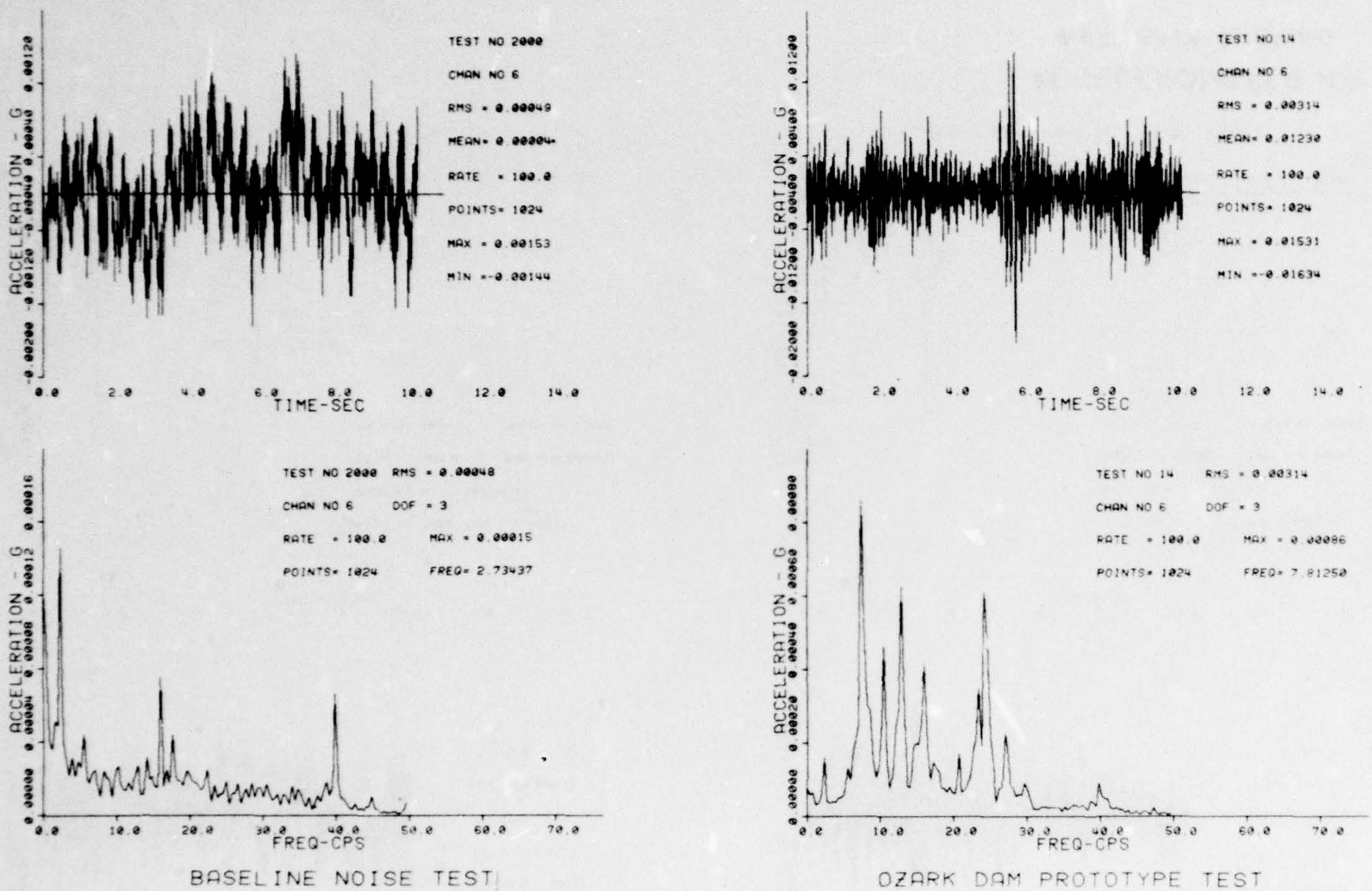
OZARK DAM PROTOTYPE TEST

ACCELEROMETER 4H

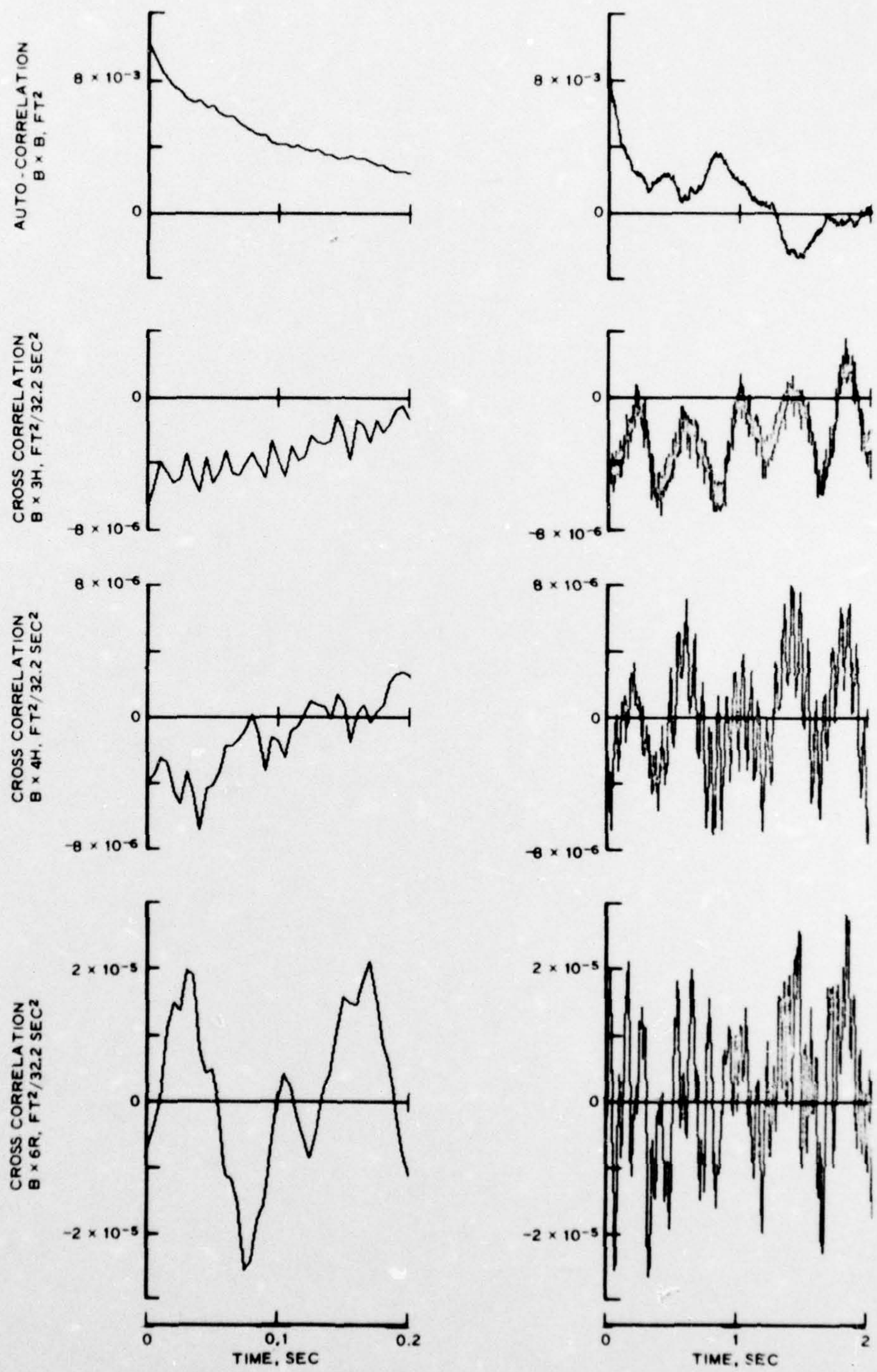
8-FT GATE OPENING

PLATE 13

PLATE 14



ACCELEROMETER 6R
8-FT GATE OPENING



NOTES:
1. SAMPLING RATE = 200 SAMPLES/SEC
2. NUMBER OF SAMPLES = 1024
3. B IS A PRESSURE TRANSDUCER; 3H, 4H, AND 6R ARE ACCELEROMETERS (SEE PLATE 1)
4. THIS MATERIAL IS DISCUSSED IN PARA 33 TEXT

CORRELATIONS
TEST 14, 8-FT GATE OPENING

APPENDIX A: NOTATION

A	$5.75U^*$; flow area
b/B	Gate opening versus head ratios
B	$U^*(8.5 - 5.75 \log K_s)$
c'_f	Local skin friction coefficient
C_c	Contraction coefficient
g	Acceleration, ft/sec^2
h	Piezometric head, ft
K_s	Equivalent sand grain roughness, ft
L	Effective spillway crest length, ft
N	Number of spaces between the streamlines
o	Subscript denoting a reference condition
q	Discharge per unit width, ft^2/sec
Q	Total discharge, ft^3/sec
R_1, R_2	Peak-to-peak range during a sample period (see paragraph 35)
R_x	Reynold's number
U	Local velocity, ft/sec
U_∞	Free stream velocity, ft/sec
U^*	$\sqrt{\tau o/\rho}$ where τo is the boundary shear stress, lb/ft^2, and ρ is the fluid density, slug/ft^3
V	Velocity, ft/sec
X	Distance downstream from the leading edge of the spillway
y	Distance from wall, ft
β	Angle of convergence
δ	Theoretical boundary layer thickness, ft

Δn	Flownet grid interval, ft
ν	Kinematic viscosity, ft^2/sec
ρ	Density, $slug/ft^3$
τ_o	Boundary shear, lb/ft^2

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Pugh, Clifford A

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Prepared for U. S. Army Engineer District, Little Rock, Little Rock, Arkansas.

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